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Exploring Ozonated Mist as a Disinfection Method via Simulation-Based Evaluation

Danial Hakim Rahmat[1], Fauziah Jerai[1,2*], Ahmad Hanaa' Farhan[1], Nor Afifah Yahaya[1], Amizon Azizan[3], Amanatuzzakiah Abdul Halim[4], Khairul Faezah Md Yunos[5]

[1]Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, 40450 Selangor, Malaysia
[2]Wind Engineering & Building Physics (WEBP), Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, 40450 Selangor, Malaysia
[3]Faculty of Chemical Engineering, Universiti Teknologi MARA, Shah Alam, 40450 Selangor, Malaysia
[4]Department of Chemical Engineering and Sustainability, Faculty of Engineering, International Islamic University Malaysia (IIUM), 53100 Kuala Lumpur, Malaysia
[5]Department of Process and Food Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Selangor, Malaysia

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ABSTRACT

In recent years, ozone has gained popularity as a powerful disinfectant and sanitizer. As it can transform into harmless oxygen and disinfect challenging areas, it's a great disinfectant option for healthcare settings, such as an ambulance. However, ensuring the ambulance is fully sanitized is crucial because the ozone water mist needs to be distributed without human intervention; hence, an ozone generator with self-activation is applied to disinfect the air and surfaces. Furthermore, assessing ozone's efficacy and distribution in a sanitization system remains in a preliminary phase, highlighting the importance of studying the behavior, visualization, and efficiency of ozone mist. This study provides a transient Computational Fluid Dynamics (CFD) simulation of ozone mist dispersion in a small, enclosed space possessing minimal air outlets. Unlike steady-state models that only capture peak exposure conditions, the time-dependent approach used here allows for observation of both the build-up and subsequent decline of ozone concentration over time. The simulation results show that ozone levels rise rapidly during the first 60 seconds due to mist generation and then begin to decrease as the ozone decays and escapes through the small opening. This behavior closely resembles actual disinfection scenarios, in which regulated ozone emissions must be followed by adequate decay or ventilation before re-entry. By integrating boundary leakage and transient modeling, the research provides a significant understanding of how operational timing influences ozone retention and dispersion. These findings play a significant role in the progression of safer ozone-based disinfection

[1*] Corresponding author. *E-mail address*: fauziahjerai@uitm.edu.my
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techniques, especially in mobile treatment environments such as ambulances.

INTRODUCTION

The powerful oxidizing nature of ozone (O_3), a molecule composed of three oxygen atoms, makes it a great disinfectant and hygiene agent (Vitali & Valdenassi, 2019). In the last few years, the adoption of ozone for sanitizing purposes has attracted considerable interest, notably in areas where sanitation is vital, such as medical centres and rescue vehicles (Epelle et al., 2022). The power of ozone in neutralizing various pathogens, comprising bacteria, viruses, and fungi, highlights its potential as a fantastic alternative to typical chemical disinfectants (Wang et al., 2022). By producing ozone mist, establishments can accomplish comprehensive surface disinfection without the detrimental residues often linked to traditional sanitizers. This groundbreaking method not only improves sanitation protocols but also fosters a safer atmosphere for both patients and healthcare practitioners, particularly during the transportation of individuals with infectious illnesses (Muley et al., 2020).

Ozone is flexible in both vapor and liquid forms, thus proving useful for water treatment and disinfecting surfaces. One notable application of ozone water in the form of mist is its role in water treatment, which incorporates the distribution of ozone gas in fine droplets or particles to disinfect and elevate water quality, yielding advantages, including robust disinfection efficacy, oxidation of organic compounds, and reduction of taste and odour problems (Evans et al., 2003; Rosdi et al., 2024). Additionally, academic inquiries have shown that while it is chiefly utilized for water treatment, it is likewise capable of eliminating molds, bacteria, and fungi, as well as inactivating viruses on a variety of surfaces and in aerosols present in the atmosphere (Torres-Mata et al., 2022). Besides that, an extensive review was done by Grignani et al. (2021) on the role of ozone as an air and surface disinfectant in the conjuncture of COVID-19. They concluded that ozone at a low concentration is a powerful agent for the disinfection of air, surfaces, and some personal protection devices. Furthermore, ozone does not leave chemical residues, making it an environmentally friendly option for sanitization. It serves a function in food hygiene aimed at the elimination of pathogens without detracting from the organoleptic qualities of food, thereby sustaining both quality and safety (Tzortzakis, 2016). While ozone water and mist confer significant advantages as sanitizing solutions, their use must be managed with caution to avoid potential health and safety dangers. The concentration and exposure time of ozone need to be optimized to ensure efficacy without causing harm to personnel or the environment.

To minimize health risks related to ozone exposure in closed environments, a careful analysis of ozone levels and exposure periods is necessary (Gopikrishnan et al., 2025). The standard approach of measuring ozone concentration often involves the use of chemical sensors or sampling devices that require physical presence in the environment being monitored (Samsudin et al., 2017). These methods can be fraught with risks and high costs due to several factors, namely safety risk, high cost, labor-intensive, and limited spatial coverage (Pang et al., 2017). In contrast, Computational Fluid Dynamics (CFD) offers an alternative approach to measuring ozone concentration that can lessen these risks and reduce costs. The initial investment in CFD software can be offset by the reduction in equipment and personnel costs over time (Khalid et al., 2025). Furthermore, CFD can be integrated with real-time monitoring systems, allowing for continuous assessment of ozone levels (Stoelle et al., 2021). This capability enables immediate modifications to the disinfection process if concentrations exceed safe thresholds, further enhancing safety and effectiveness.

The literature assessment on past research on ozone movement in closed settings through Computational Fluid Dynamics (CFD) analysis presented several remarkable papers, each delivering key insights into the role and spread of ozone for sanitization. To begin with, CFD enables the analysis of gas flow distribution, yielding important information regarding the efficient use of gas, particularly ozone, for

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disinfection and its dynamics under different environmental conditions (Ioannidis et al., 2025). This approach is essential for maximizing ozone utilization across various environments, including hospital rooms, public transport, and residential areas. In medical facilities, CFD simulations have been utilized to examine the dispersion of ozonized mist for sanitization purposes (I. Anton Schroer et al., 2022). The study found that ozone concentrations were higher near the generator and decreased with distance, achieving effective sanitization levels within a short time frame. For public transport, CFD models have been developed to predict ozone concentration and its efficacy in disinfecting surfaces. These models have been validated with empirical tests, showing high disinfection rates for viruses similar to SARS-CoV-2 (Falcó et al., 2021). CFD simulations in residential settings have shown that ozone concentrations can vary significantly based on the orientation of the house and the floor level, with higher concentrations observed on upper floors. This has implications for indoor air quality and health risks, particularly for children (Zhang et al., 2023).

Ambulances often have lingering odors from various medical procedures and patient situations, making their removal an arduous task. Due to that, ambulance staff and patients are exposed to different airborne pollutants during emergency transport, including airborne pathogens and volatile organic compounds. Ozone mist has been shown to effectively reduce microbial contamination, making it a promising candidate for enhancing sanitation protocols in ambulances used for COVID-19 patients (Gómez-Castillo et al., 2023). However, its high reactivity and potential health risk elevated concentrations make it essential to carefully control its distribution within enclosed spaces. Furthermore, although ozone is increasingly used for disinfection in enclosed environments such as ambulances, limited research has focused on its transient concentration behavior in spaces with small openings or imperfect sealing. Most existing studies rely on steady-state models or assume completely airtight conditions (Shi et al., 2020), which do not accurately reflect the leakage and ventilation characteristics typical of real ambulance interiors. This creates a gap in understanding how ozone builds up, distributes, and decays over time under realistic conditions. In particular, the effect of minor air exchange on ozone retention and safety thresholds remains underexplored.

In response to that matter, the purpose of this study is to simulate the time-dependent concentration profile of ozone mist in an ambulance-like environment with a small air outlet. By modeling both the increase phase during mist generation and the natural decay afterward, the study aims to evaluate how space leakage influences ozone distribution, disinfection effectiveness, and safe reentry timing. The results are intended to support practical decision-making in generator placement, misting duration, and ventilation strategy for mobile medical disinfection.

METHODOLOGY

Physical Model

In the first step, before starting the CFD simulation is pre-processing to characterize the parameters of the model and the simulation. This includes characterizing the geometry, which creates a three-dimensional model using Ansys: Space Claim as shown in Fig 1 below. The geometry of the ambulance cabin is constructed with the measurement of 3 m length, 1.9 m wide, and a height of 1.8 m. The geometry is also designed with simple equipment consisting of two chairs and a stretcher, which is all set in the name selection. Next, the inlet boundary condition will be determined, which will act as the entrance for the ozone mist to be diffused inside the ambulance cabin, while a small ventilation slit will be set as the outlet, which will act as ventilation for the ozone mist to flow out of the ambulance. The inlet for the ozone mist was designed with measurements of 0.4 m by 0.15 m and a thickness of 0.05 m, while an outlet measuring 1.88 m in length, 0.2 m in width, and 0.2 m in thickness was constructed at the bottom of the back wall.

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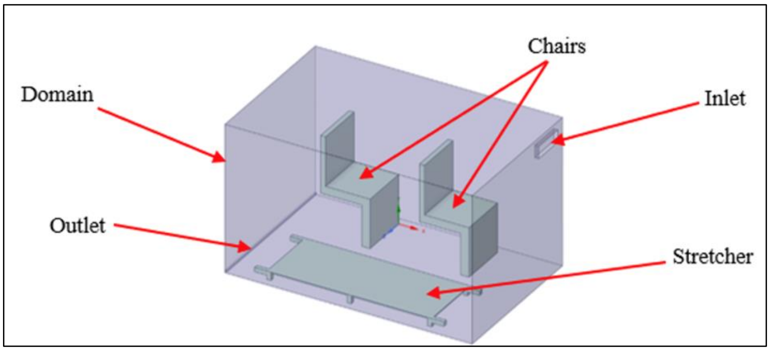

Fig. 1. Geometry constructed on ANSYS space claim.

Mathematical Model

To simulate the transient dispersion of ozone mist inside an ambulance cabin, ANSYS Fluent's embedded mathematical models were employed to capture both fluid dynamics and species transport phenomena. The airflow was governed by the unsteady incompressible Navier–Stokes equations, which express the conservation of mass and momentum. Turbulence effects were modelled using the realizable k-ε model, which provides improved accuracy for complex internal flows with recirculation and streamline curvature (Isa et al., 2019). Ozone concentration was predicted using the species transport model, which solves the convection-diffusion equation for chemical species. This combination of models enabled accurate transient tracking of ozone concentration evolution and retention within the semi-enclosed space of the ambulance (Falcó et al., 2021). The details of the governing equation can also be referred from Tamaddon Jahromi et al. (2021).

To simplify the analysis and focus on spatial distribution effects, several assumptions were made in this study. First, the ozone mist was modelled as a continuous gaseous phase using the species transport model, without accounting for liquid droplet dynamics. This means that the mist, although composed of tiny water droplets with ozone, is incorporated in the simulation as a dense gas mixture. This characteristic is frequently observed in mists composed of particles below 10 µm, for example, ultrafine water mists used for firefighting (Adiga et al., 2007). In this simulation, the properties of the ozone mist, including its density and mass diffusivity, are set similar to those of water vapor to match the droplet dynamics. This method simplifies the problem by using a species transport model to calculate concentration changes over time, instead of tracking individual droplets with a Lagrangian or discrete particle method.

Furthermore, the simulation is conducted in a transient within setting for 300 s of active ozone misting due to the computer limitation. Airflow within the space is considered mildly turbulent, depending on the inlet condition, and no additional sources of ventilation or heat transfer are included. The space is assumed to be semi-enclosed during misting, with no occupants or external air exchange. However, an outlet was introduced on the wall opposite the ozone mist generator to facilitate convergence and maintain numerical stability during the analysis. While the actual application of ozone mist disinfection typically occurs in a sealed or semi-sealed environment to retain mist concentration and maximize surface contact, the inclusion of an outlet boundary was necessary to prevent unphysical pressure build-up and allow proper mass conservation within the computational domain (Li et al., 2016).

Boundary Condition

In this section, several parameters are specified as boundary conditions for the simulation. One key input is the inlet, where the mass flow rate is defined. This value represents the ozone distribution entering the ozone mist generator and is set to 0.018 kg/s, and ozone mist mass fraction was 0.04257, which reflects

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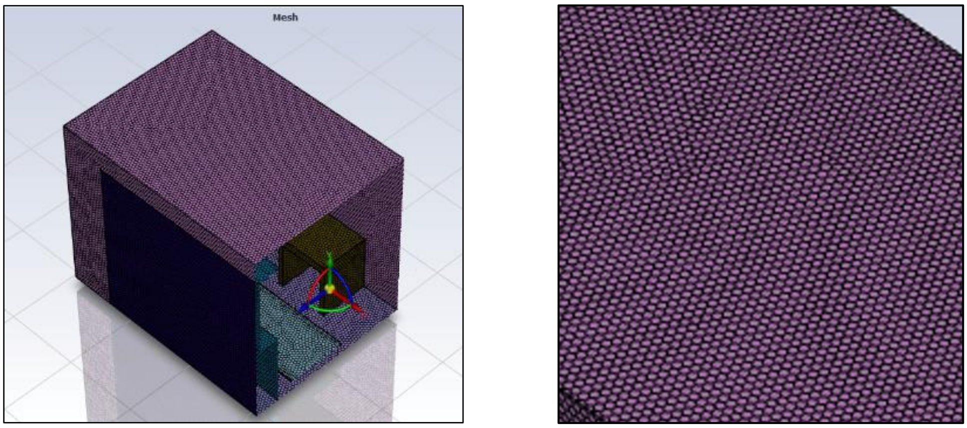
a standard operational rate for such devices (I. Anton Schroer et al., 2022). The outlet is assigned a gauge pressure of 0 Pa (gauge), representing atmospheric pressure. The working fluid is modeled as water vapor, with its properties sourced from the ANSYS Fluent materials database. Additional settings, including turbulent intensity and turbulent viscosity ratio, follow ANSYS Fluent's recommended default values. Both the inlet and outlet are assumed to be at a temperature of 300 K, and no-slip boundary conditions are applied throughout the domain.

Although the transport properties are similar to those of water vapor, the mass characteristics of the ozone mist are attributed to water. This hybrid approach had been validated by Adiga et al. (2007) and provides a more accurate representation of the mist's behavior in confined spaces, effectively bridging the gap between gas-like motion and water-based mass properties. A molar mass of 24.45 g/mol was calculated for the mist by Tian-shui et al. (2013), based on the ideal gas law applied at standard conditions (1 atm, 298 K) and an assumed density of 1000 kg/m³. The numerical solver automatically computed the thermodynamic parameters for the gas mixture, which consisted of air, ozone-enriched mist, and ozone-depleted mist. The mixture's viscosity was determined using a standard mixing rule, while its density was assumed to follow ideal gas behavior. Additionally, the mass diffusivity of both ozone-containing and ozone-depleted mist in air was calculated based on kinetic theory principles.

Validation of the Computational Meshes

A mesh sensitivity study, also known as a grid independence study, is typically conducted in Computational Fluid Dynamics (CFD) simulations. For this study, the maximum cell length was selected and employed for meshing and running the simulation. The reason for this is that the maximum cell length directly impacts the mesh resolution, making it an essential parameter in any grid independence study. Three computational meshes were created using the Fluent meshing model, comprising 1.3×10^5, 4.59×10^5, and 1.22×10^6 number of cells. Poly-hexcore elements were employed, and the three grids' results were assessed via the Grid Convergence Index (GCI) method (Fig 2 (a) and (b)). The point that gives minimal advantage can be found by studying variations in average density at the stretcher location about the maximum cell length. As the mesh grows finer, there is a trend towards convergence in the average density of ozone mist at the stretcher location. As mesh refinement increases, density slightly decreases further refinement beyond 1.22×10^6 number of cells does not yield significant improvements in accuracy. The mesh containing 1.22×10^6 number of cells elements was selected for its computational efficiency and minimal impact on results (Zainudin et. al, 2023).



(a) (b)

Fig. 2. Mesh with 1.22×10^6 number of cells (a) full view (b) zoom view of the mesh refinement.

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Validation of Mathematical Model

The benchmark experimental case designated as Case 1 in the Wang & Chen (2009) article was employed for verification and validation. As it also assesses the fluid dynamics of a jet in a room, this article is appropriate for the validation of the current study. A cube-shaped chamber with a 2.44 m edge, as shown in Fig 3 serves as the experiment's setting. A slit in the room's left wall's top area (0.03 m in height) allows air to enter the domain. Another slit in the right wall (0.08 m high, close to the room floor) functions as the air exit. For this validation, measurements were taken along line 10, located 25 cm from the wall, to acquire velocity data, which allowed for the derivation of the velocity profile (*U*) and turbulent kinetic energy (TKE). The validation boundary conditions were steady state, an inlet air velocity of 1.366 m/s, and an air outlet set as a pressure outlet. The turbulence model was k-e Realizable, but with enhanced wall functions. With 2.22 x 10^5, 5.3 x 10^5, and 1.1 x 10^6 elements, three computational meshes were generated to ensure mesh independence from the results of Case 1. The GCI method was used to examine these meshes, and the average difference between the coarse and medium meshes was 2.6%, and the difference between the medium and refined meshes was 1.9%. As a result, the refined mesh was utilized to validate the results.

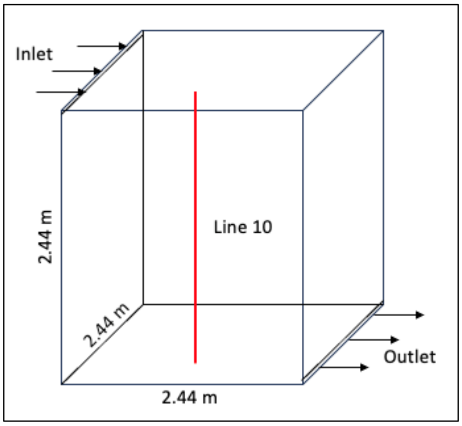

Fig. 3. The geometry used for the validation of fluid flows.

Verification of CFD Results

To ensure the reliability of the CFD simulation results, a literature-based verification method was adopted. Previous studies involving ozone dispersion in enclosed environments were reviewed to serve as benchmarks for comparison. The validation of this simulation was strengthened by comparison with the findings of Falco et al. (2021), who conducted both experimental and a transient ozone dispersion study in a tram environment that included natural ventilation through openings. Although the geometry and operational conditions differ from an ambulance, the inclusion of air exchange mechanisms makes their study particularly relevant for comparison. Their experimental exhibit a similar concentration trend with a rapid increase during the active misting phase followed by a gradual decline due to ozone decay and opening. The alignment in these time-dependent behaviors supports the credibility of the current model and demonstrates that it captures the essential physical processes governing ozone distribution in partially ventilated enclosed spaces.

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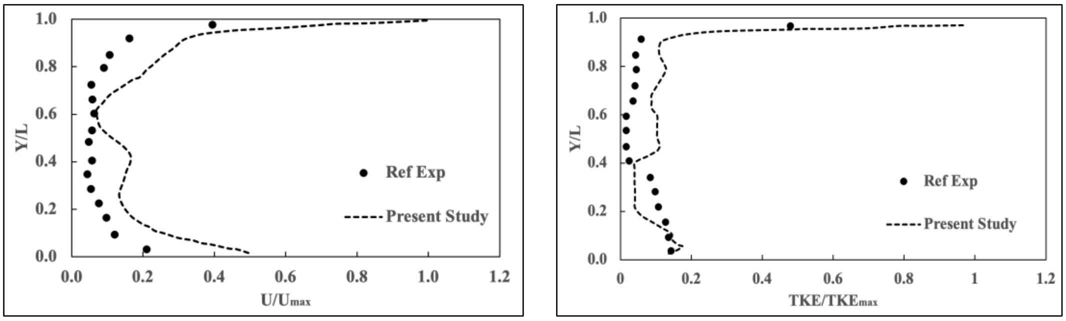
RESULTS AND DISCUSSION

Based on the post-processor stage, the visualization result will be expressed as an interpretation of the simulation to be understood. The obtained result will be assessed for the real-world ambulance and be used for further research. The result will also define the study's objective.

Validation of Mathematical Models

The accuracy of the fluid dynamic model utilized in this research was evaluated by comparing simulation outcomes of velocity and turbulent kinetic energy (TKE) against experimental findings from Wang & Chen (2009). Both datasets were normalized to enable a straightforward comparison: the height (Y) was adjusted based on the room height (L = 2.44 m), while velocity and TKE were normalized by their respective peak values (1.5 m/s for velocity and 0.05 m²/s² for TKE). The comparison, illustrated in Fig 4, reveals that the CFD solver employing the realizable k-ε turbulence model effectively captures the flow characteristics. The simulated velocity profiles correspond closely with experimental trends across control line 10, and the TKE distributions also exhibit a strong correlation with the observed experimental patterns. These findings affirm that the chosen turbulence model and simulation configuration are adequately validated and suitable for subsequent applications concerning ozone mist dispersion in the ambulance geometry.



(a) (b)

Fig. 4. The profiles of velocity (a) and TKE (b) at line 10, derived from numerical analysis in this study and experimental work by Wang & Chen (2009).

Ozone Mist Concentration Dynamics within the Ambulance Cabin

As shown in Fig 5, this study examined the ozone mist concentration in an ambulance over 300 seconds at 1-minute intervals to evaluate ozone's efficacy as a sanitizer, revealing dynamic dispersion across various surfaces. The initial 60 seconds saw peak ozone levels, with inlet concentrations at 32.39 ppm and outlet concentrations at 217.59 ppm, suggesting effective circulation within the ambulance. The ozone mist shows an initial concentration build-up near the ozone mist generator exit, followed by spatial dispersion influenced by natural convection and air leakage, mirroring the turbulent transition reported by Zulkifli et al. (2024). At 120 seconds, ozone concentrations significantly decreased to an average of 16.65 ppm; the inlet remained constant at 32.39 ppm, while the outlet fell to 6.99 ppm. This marked reduction indicates effective dispersion and dilution of the ozone mist, possibly facilitated by ventilation effects and the gradual saturation of the internal volume. At 180 seconds, the average concentration reached 41.03 ppm. Concentrations on various surfaces rose significantly, indicating a high density of ozone mist and effective dispersion. This phase highlights the transient behavior of the ozone mist, with concentration values fluctuating over time.

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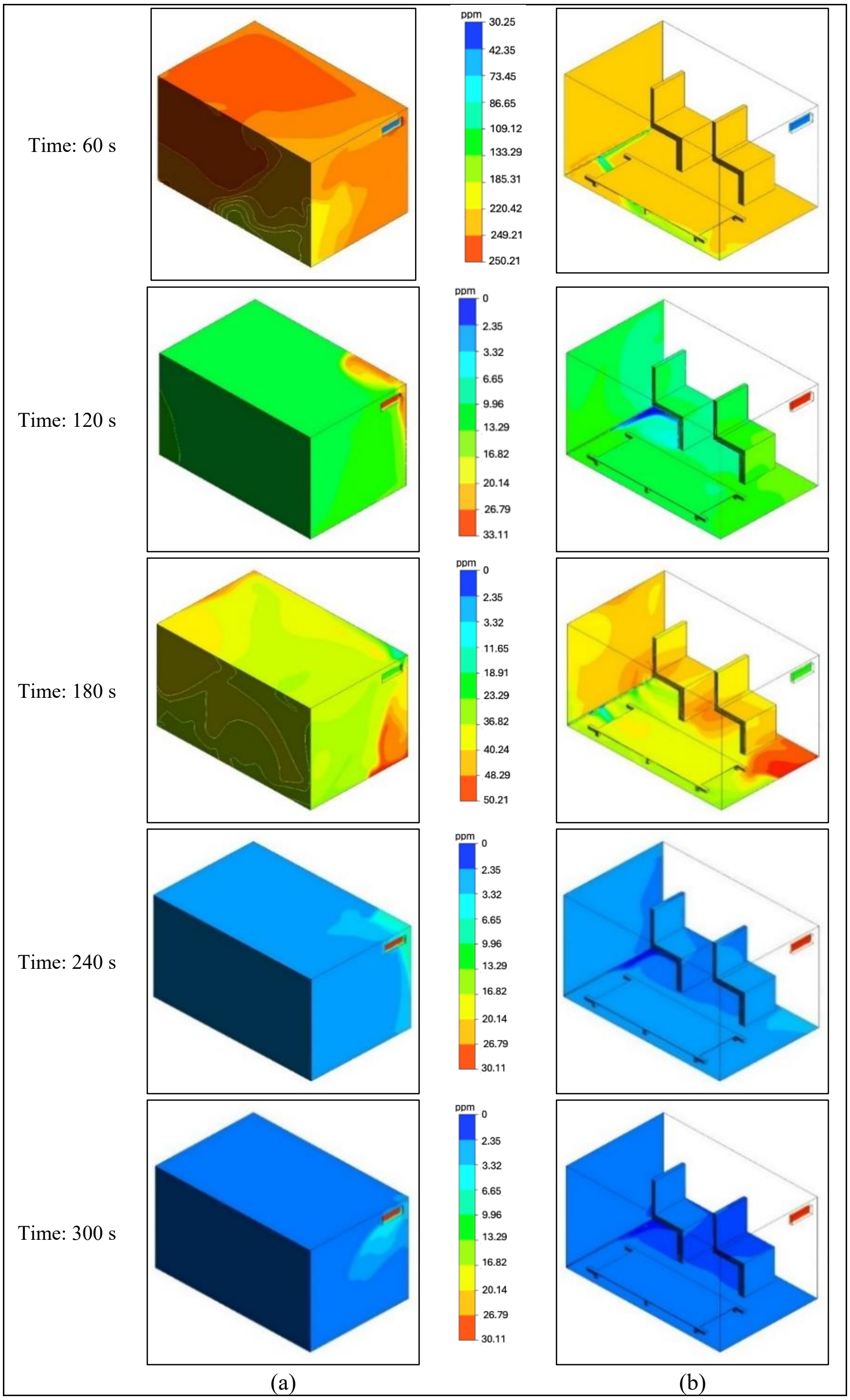

Fig. 5. Ozone concentration at 60 s, 120 s, 180 s, 240 s, and 300 s (a) domain view, and (b) interior view.

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While the substantial drop in surface ozone concentration at 240 seconds was initially attributed to mist escape through the outlet, the low outflow concentration (1.92 ppm) suggests that other mechanisms are likely more dominant. Natural decomposition of ozone in a moist and semi-confined space, combined with internal diffusion and dilution, are probable contributor to the observed decline (Giordano, 2020). At 300 seconds, the inlet ozone concentration remained stable at 32.39. The outlet concentration of 1.42 ppm suggests a stable depletion of ozone within the ambulance. The concentrations measured on various surfaces range from 2.91 ppm to 3.85 ppm, indicating a trend towards consistent depletion of ozone mist.

These findings highlight the transient and non-linear behaviour of ozone mist dispersion. The observed fluctuations over time reflect a dynamic balance between generation, accumulation, and ventilation-driven loss. Overall, the results confirm that ozone mist can effectively penetrate and saturate enclosed environments such as ambulance interiors, supporting its potential application as a disinfection strategy. Fig 6 illustrates the changes in the concentration of ozone at different places of a closed area during the 300 seconds. These areas are the inlet, outlet, front and back wall, side wall, roof and floor, chair, and stretcher. Initially, all regions, except the inlet, showed a rise in ozone concentration during the first 60 seconds, after which a steady decline was observed, despite the continuous generation of ozone. This trend can be attributed to the balance between ozone generation and its physical transport out of the domain through the small outlet, which was introduced to aid numerical convergence (Li et al., 2016). While ozone initially accumulated within the system, over time, the rate of loss primarily via outlet transport exceeded the generation rate. On the other hand, the inlet remained at a constant concentration of 32.39 ppm, which is in consonant with the location of the ozone being supplied. The input concentration for the ozone generator was adopted from I. Anton Schroer et al. (2022), who conducted their study in a controlled test chamber simulating a healthcare environment, where ozone concentration at the generator outlet was measured at approximately 32 ppm. This alignment reinforces the appropriateness of our inlet boundary condition and validates our selection based on real-world operating.

At 120 seconds, the decrease in average ozone concentration indicates that the mist had dispersed from the inlet region and was undergoing dilution as it mixed with ambient air. However, by 180 seconds, localized increases in ozone concentration on various surfaces were observed. This suggests that the mist continued to disperse spatially and reached new regions within the ambulance interior, leading to a rise in surface concentrations despite the overall volumetric average decreasing earlier. In this context, dispersion initially caused dilution, but over time resulted in more uniform and effective ozone coverage across surfaces. While the substantial drop in surface ozone concentration at 240 seconds was initially attributed to mist escape through the outlet, the low outflow concentration (1.92 ppm) suggests that other mechanisms are likely more dominant. Natural decomposition of ozone in a moist and semi-confined space, combined with internal diffusion and dilution, are probable contributor to the observed decline.

Although the current simulation spans only five minutes, the transient ozone concentration profile observed aligns qualitatively with the trend reported by Falco et al. (2021), who studied ozone dynamics in a tram with natural ventilation. In their study, ozone concentration decreased after an initial rise at around 2 minutes, showed a secondary increase at approximately 4 minutes, and began a long-term decay phase after 20 minutes. Similarly, in the present study, the simulated concentration rises during the first 60 seconds due to mist injection, decreases by 120 seconds likely due to dispersion and partial leakage, and then shows a brief secondary increase before entering a decay phase after 180 seconds. Although the absolute durations differ due to system scale and injection parameters, the non-monotonic behavior observed in both studies supports the validity of the model in capturing realistic ozone transport and re-circulation in semi-enclosed, ventilated environments. This comparison strengthens confidence in the simulation results, particularly for short-term dynamics relevant to mobile disinfection protocols.

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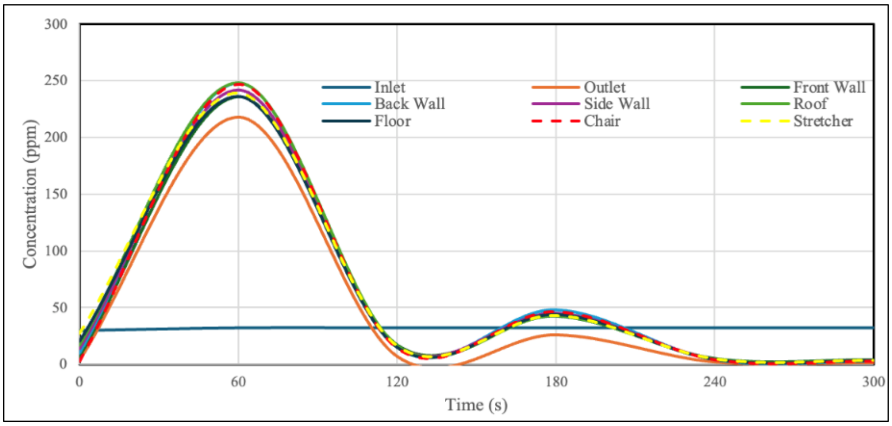

Fig. 6. Transient profile of the ozone mist concentration.

OSHA Standards for Ozone Exposure

While ozone is a highly effective disinfectant, its application must be carefully controlled to balance efficacy with safety. The optimal concentration for sanitizing an ambulance appears to be around 25 ppm for 30 minutes, but this may vary depending on the specific microbial load and environmental conditions (Gómez-Castillo et al., 2023). Cleaning the impacted area is of utmost importance, yet we must also follow safety measures to mitigate ozone exposure, thus guaranteeing that disinfection efforts do not adversely affect health. The Occupational Safety and Health Administration (OSHA) sets permissible exposure limits to protect workers from the harmful effects of ozone exposure in various occupational settings (OSHA, 1999). OSHA Standards for Ozone exposure specifically, the U.S. Occupational Safety and Health Administration defines a permissible exposure limit (PEL) of 0.1 ppm for ozone over an 8-hour time-weighted average.

To contextualize the safety and effectiveness of the ozone mist disinfection strategy, the results were compared with OSHA's permissible exposure limits (PEL) for ozone. OSHA limits exposure to 0.1 ppm over an 8-hour time-weighted average. The simulated ozone concentrations in this study were significantly higher, reaching peaks above 200 ppm at certain locations during the first 60 seconds. These elevated levels are intended solely for disinfection during unoccupied conditions and far exceed occupational safety thresholds. The simulation was limited to a short duration of 300 seconds, aligning with disinfection cycles in practice where personnel are not present. The ozone decay over time and the reduction of surface concentrations to below 10 ppm by 300 seconds suggest that safe re-entry is achievable following an appropriate ventilation period. Therefore, although the selected parameters exceed OSHA's occupational exposure limits, they are justified for short-term, high-concentration disinfection scenarios, provided that access. However, it is important to remember that, in a real-world situation, this leak would pollute the area surrounding the ambulance, which is typically near the healthcare facility. This serves as a reminder that a specific standard operating procedure must be established during the sanitization process to mitigate potential health risks to ambulance users, including healthcare facility personnel and patients. Or else, to lessen health risks linked to improper handling during sanitization, a viable alternative would be to combine ozone with various disinfection strategies, such as ultraviolet light, so that sanitization efficiency can be increased and simultaneously reduce the amount of ozone applied (Samsudin et al., 2017).

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CONCLUSION

This study investigated the transient behavior of ozone mist concentration in a semi-enclosed ambulance-like environment with a small opening, using a fixed ozone generator position. The simulation revealed a non-linear concentration pattern—initial increase, followed by partial decay, a secondary rise, and eventual dissipation—demonstrating realistic ozone dynamics over a short operational period. These results align qualitatively with trends observed in the literature, supporting the model's validity. Although the nozzle position was not varied, the findings highlight how even a single-point ozone release interacts with spatial flow and leakage to affect overall concentration levels. This has important implications for ensuring effective disinfection while managing exposure risks in mobile healthcare settings.

While simulation offers useful insights into short-term ozone dynamics, the lack of experimental data and simplification of leakage flow are noted limitations. Future studies should incorporate sensor-based measurements to validate results and explore longer-term behavior under varying environmental conditions. Overall, this study provides a foundational understanding for optimizing ozone-based disinfection strategies in emergency medical settings. Ultimately, the insights from this research provide a scientific foundation for practical decision-making in mobile healthcare settings, aiding in the development of safer and more effective ozone-based disinfection protocols.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefit, commercial or financial conflicts, and declare the absence of conflicting interests with the funders.

AUTHORS' CONTRIBUTIONS

Danial Hakim Rahmat: formal analysis, investigation, methodology, writing-Original Draft; Fauziah Jerai: supervision, conceptualization, methodology, validation, writing-review and editing, resources; Ahmad Hanaa' Farhan: formal analysis, investigation, methodology, writing; Nor Afifah Yahaya: reviewing and editing; Amizon Azizan: reviewing and editing; Amanatuzzakiah Abdul Halim: reviewing and editing; Khairul Faezah Md Yunos: reviewing and editing.

REFERENCE

Adiga, K. C., Hatcher Jr, R. F., Sheinson, R. S., Williams, F. W., & Ayers, S. (2007). A computational and experimental study of ultra fine water mist as a total flooding agent. Fire Safety Journal, 42(2), 150-

https://doi.org/10.24191/jmeche.v22i3.6707

160. https://doi.org/10.1016/j.firesaf.2006.08.010

Anton Schroer, I., Da Silva, J., Brochier, B., Da Silva, P. R. S., Da Silva, S. B., & Hansen, É. (2023). Study of ozone misting for sanitization of hospital facilities: A CFD approach. Ozone: Science & Engineering, 45(3), 305-319. https://doi.org/10.1080/01919512.2022.2091512

Epelle, E. I., Macfarlane, A., Cusack, M., Burns, A., Okolie, J. A., Mackay, W., Rateb, M., & Yaseen, M. (2023). Ozone application in different industries: A review of recent developments. Chemical Engineering Journal, 454(2), 140188. https://doi.org/10.1016/j.cej.2022.140188

Evans, H., Bauer, M., Goodman, N., Hague, J., & Ta, T. (2003). The role of ozone in improving drinking water quality in London and Oxford. Ozone: Science & Engineering, 25(5), 409–416. https://doi.org/10.1080/01919510390481739

Falco, I., Randazzo, W., Sanchez, G., Vilarroig, J., Climent, J., Chiva, S., Chica, A., & Navarro-Laboulais, J. (2021). Experimental and CFD evaluation of ozone efficacy against coronavirus and enteric virus contamination on public transport surfaces. Journal of Environmental Chemical Engineering, 9(5), 106217. https://doi.org/10.1016/j.jece.2021.106217

Giordano, A. (2020). CFD simulation of an aerosol mixing chamber [Master's thesis, Swiss Federal Technology Institute of Lausanne (EPFL)]. Retrieved from https://empir.npl.co.uk/aerotox/wp-content/uploads/sites/53/2021/01/Giordano_Master_Thesis.pdf

Gómez-Castillo, M. A., Rivera Romero, C., Reátegui-Ochoa, K., Mamani Zapana, E., & Silva-Jaimes, M. (2023). Ozone efficacy for the disinfection of ambulances used to transport patients during the COVID-19 pandemic in Peru. International Journal of Environmental Research and Public Health, 20(10), 5776. https://doi.org/10.3390/ijerph20105776

Gopikrishnan, G. S., Ardra, T. S., & Kuttippurath, J. (2025). Exposure to surface ozone and its associated health effects and economic burden in India. Global Transitions, 7, 148-158. https://doi.org/10.1016/j.glt.2025.03.002

Grignani, E., Mansi, A., Cabella, R., Castellano, P., Tirabasso, A., Sisto, R., Spagnoli, M., Fabrizi, G., Frigerio, F., & Tranfo, G. (2021). Safe and effective use of ozone as air and surface disinfectant in the conjuncture of Covid-19. Gases, 1(1), 19-32. https://doi.org/10.3390/gases1010002

Ioannidis, G., Tremper, P., Li, C., Riedel, T., Rapkos, N., Boikos, C., & Ntziachristos, L. (2025). Evaluating the spatial coverage of air quality monitoring stations using computational fluid dynamics. Atmosphere, 16(3), 326. https://doi.org/10.3390/atmos16030326

Isa, K. M., Osman, K., Yahya, A., Ghaffar, Z. A., Hamid, A. H. A., & Kasolang, S. (2019). Studies on the spray characteristics of pressure-swirl atomizers for automatic hand sanitizer application. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 55(1), 51-64.

Khalid, A. A. A. M., Jerai, F., Zainuddin, N. A. M., Abbas, N. M., & Razak, A. A. (2025). CFD investigation of toluene emission in a printing room. CFD Letters, 17(5), 90-102. https://doi.org/10.37934/cfdl.17.5.90102

Li, X. J., Zhou, R. P., & Konovessis, D. (2016). CFD analysis of natural gas dispersion in engine room space based on multi-factor coupling. Ocean Engineering, 111, 524-532. https://doi.org/10.1016/j.oceaneng.2015.11.018

Mohd Zainuddin, N. A., Jerai, F., Abd Razak, A., & Mohamad, M. F. (2023). Accuracy of CFD simulations on indoor air ventilation: Application of grid convergence index on underfloor air distribution (UFAD) system design. Journal of Mechanical Engineering, 20(3), 199-222.

https://doi.org/10.24191/jmeche.v20i3.23908

Muley, D., Shahin, M., Dias, C., & Abdullah, M. (2020). Role of transport during outbreak of infectious diseases: Evidence from the past. Sustainability, 12(18), 7367. https://doi.org/10.3390/su12187367

Occupational Safety and Health Administration (OSHA). (1999). TABLE Z-1 Limits for air contaminants (1910.1000 Table Z-1). U. S. Department of Labor.

Pang, X., Shaw, M. D., Lewis, A. C., Carpenter, L. J., & Batchellier, T. (2017). Electrochemical ozone sensors: A miniaturised alternative for ozone measurements in laboratory experiments and air-quality monitoring. Sensors and Actuators B: Chemical, 240, 829-837. https://doi.org/10.1016/j.snb.2016.09.020

Rosdi, N. A., Sha'ary, A. R., Nor, Y. A., Jimat, D. N., & Tshai, K. Y. (2024). Stability analysis of immobilized ozonated vegetable oil on silica nanoparticles. Chemical and Natural Resources Engineering Journal, 8(2), 78-91.

Samsudin, N., Hashim, Y. Z. H. Y., Arifin, M. A., Mel, M., Salleh, H. M., Sopyan, I., & Jimat, D. N. (2017). Optimization of ultraviolet ozone treatment process for improvement of polycaprolactone (PCL) microcarrier performance. Cytotechnology, 69, 601-616.

Shi, Z., Bai, J., & Han, Y. (2020). Distribution of ozone and its volatiles in indoor environment: a numerical simulation with CFD for the aircraft cabin. Environmental Technology, 41(24), 3146–3156. https://doi.org/10.1080/09593330.2019.1600044

Tamaddon Jahromi, H., Rolland, S., Jones, J., Coccarelli, A., Sazonov, I., Kershaw, C., Tizaoui, C., Holliman, P., Worsley, D., Thomas, H., & Nithiarasu, P. (2022). Modelling ozone disinfection process for creating COVID-19 secure spaces. International Journal of Numerical Methods for Heat & Fluid Flow, 32(1), 353-363. https://doi.org/10.1108/hff-12-2020-0797

Tian-shui, L., Zhong-lin, L., Xiu-kun, X., Siu-ming, L., Guang-xuan, L., & Wei, Z. (2013). Experimental and numerical study of fire suppression performance of ultral-fine water mist in a confined space. Procedia Engineering, 52, 208-213. https://doi.org/10.1016/j.proeng.2013.02.128

Torres-Mata, L. B., García-Pérez, O., Rodríguez-Esparragón, F., Blanco, A., Villar, J., Ruiz-Apodaca, F., Martín-Barrasa, J. L., González-Martín, J. M., Serrano-Aguilar, P., Piñero, J. E., Córdoba-Lanús, E., Lorenzo-Morales, J., & Clavo, B. (2022). Ozone eliminates SARS-CoV-2 from difficult-to-clean office supplies and clinical equipment. International Journal of Environmental Research and Public Health, 19(14), 8672. https://doi.org/10.3390/ijerph19148672

Tzortzakis, N. (2016). Ozone: A powerful tool for the fresh produce preservation. In M. W. Siddiqui, J. F. A. Zavala & C. A. Hwang (Eds.), Postharvest Management Approaches for Maintaining Quality of Fresh Produce. Springer. https://doi.org/10.1007/978-3-319-23582-0_11

Vitali, G., & Valdenassi, L. (2019). Use of ozone in water, agriculture and zootechnics: Relationships between dysbiosis and mental disorders. Ozone Therapy, 4(1), 8-19. https://doi.org/10.4081/ozone.2019.8182

Wang, M., & Chen, Q. (2009). Assessment of various turbulence models for transitional flows in an enclosed environment (RP-1271). HVAC&R Research, 15(6), 1099–1119. https://doi.org/10.1080/10789669.2009.10390881

Wang, Y., Qiao, X., & Wang, Z. (2022). Application of ozone treatment in agriculture and food industry. A review. INMATEH-Agricultural Engineering, 68(3), 861-872. https://doi.org/10.35633/inmateh-68-86

https://doi.org/10.24191/jmeche.v22i3.6707

Zhang, Q., Li, L., Braham, W. W., & Ma, N. (2023). Resilient housing and climate change: analysis of ozone spatial variations based on experimentally validated CFD simulations. Proceedings of Building Simulation 2023: 18th Conference of IBPSA (pp. 418-425). IBPSA Publications. https://doi.org/10.26868/25222708.2023.1472

Zulkifli, Z., Halim, N. H. A., Solihin, Z. H., Fauzee, N. F. M., & Hadi, M. A. (2024). Predictive model and optimisation of MQL mist flow velocity through CFD analysis. International Journal of Integrated Engineering, 16(6), 294-309.

https://doi.org/10.24191/jmeche.v22i3.6707