# ADVANCING OZONE TECHNOLOGY: APPLICATIONS IN HAND SANITIZERS, COSMETICS, AND COMPUTATIONAL FLUID DYNAMICS (CFD) MODELLING FOR ENHANCED PERFORMANCE

**AMANATUZZAKIAH ABDUL HALIM[1*], YUSILAWATI AHMAD NOR[1], FAUZIAH JERAI[2], NUR AMIRA ROSDI[1], DZUN NORAINI JIMAT[1],**

*[1]Department of Chemical Engineering and Sustainability, Faculty of Engineering, International Islamic University Malaysia (IIUM), Kuala Lumpur, Malaysia*
*[2] Faculty of Mechanical Engineering, Universiti Teknologi MARA, Shah Alam, 40450 Selangor, Malaysia*

** Corresponding author: amana@iium.edu.my*

***ABSTRACT:*** Ozone technology has emerged as a revolutionary tool in disinfection, cosmetics, and process optimization. This review highlights advances in ozone applications, focusing on its role as a disinfectant in hand sanitizers and cosmetic formulations, and on its optimization using Computational Fluid Dynamics (CFD) modelling. Ozone-based hand sanitizers provide an effective, skin-friendly alternative to alcohol-based products, addressing concerns about dryness and irritation while ensuring broad-spectrum antimicrobial activity. In cosmetics, ozonated oils are recognized for their healing, moisturizing, and antimicrobial properties and are used in diverse skincare formulations. The integration of CFD modelling has significantly improved the efficiency of ozone systems by enabling precise predictions of ozone mist behavior, ensuring safety and optimal disinfection in various environments. This review highlights the potential of ozone technology as a sustainable and versatile solution for enhancing public health and safety while paving the way for innovative applications in multiple industries.

***KEY WORDS:*** *Ozone, Hand sanitizer, Ozonated water, Ozonated oil, and Antimicrobial.*

## 1. INTRODUCTION

Ozone ($O_3$) is a triatomic oxygen molecule known for its highly pungent odor and exceptional oxidizing capacity, making it a potent yet safer alternative to chemical disinfectants that may produce harmful byproducts. With a boiling point of -112°C, molecular weight of 48, and density of 2.14 g/L (at 0°C, 101.3 kPa), ozone is denser than air and tends to accumulate near the ground in enclosed spaces [1]. Due to its instability, ozone must be generated on-site and decomposes rapidly in both air and water into oxygen and reactive hydroxyl radicals, as described by its oxidation potential of 2.07 V [2]. Its solubility in water is significantly higher than oxygen, enabling swift reactions with biomolecules, yet it remains highly unstable in aqueous form, with only half its activity persisting after 20 minutes in ambient conditions [3]. As a strong oxidizing agent, 1.5 times more potent than chlorine, ozone is effective for sanitizing spaces, materials, food, and water, but its application must be controlled, as exposure above 1 ppm for extended periods can cause severe respiratory and ocular irritation [4].

Ozone is a powerful disinfectant whose effectiveness is determined by several key factors, including environmental conditions, the physical and chemical properties of the target material or substrate, and the operational parameters of the ozonation process. Parameters such as pH, temperature, pressure, and relative humidity significantly affect its antimicrobial efficiency, as does the physical structure of the substrate, including porosity and contamination state (wet, dried, or droplet). The type of microorganism, ozone generation method, exposure dosage, and duration also play critical roles in determining the success of the treatment. Studies have shown that ozone outperforms other disinfectants like chlorine dioxide, sodium hypochlorite, and chloramine, achieving a sterility assurance level of up to $10^{-6}$ against a wide range of microorganisms, including highly resistant species *like Geobacillus stearothermophilus* [4].

The antimicrobial action of ozone involves both direct and indirect mechanisms. Direct inactivation occurs via electrophilic attack, whereas indirect action involves reactive oxygen species (ROS) generated during ozone decomposition in air or water. These ROS, including hydroxyl radicals ($OH^{-1}$), superoxides, and peroxides, disrupt cellular structures by reacting with essential biomolecules. Ozone targets the polyunsaturated fatty acids in cell membranes, initiating lipid peroxidation and forming malondialdehyde (MDA), which triggers further membrane damage [5]. This process compromises cell osmotic stability, metabolism, and integrity, ultimately leading to cellular lysis [6]. Research has demonstrated structural alterations in microorganisms like *E. coli*, *S. aureus*, and *C. albicans*, such as roughened surfaces, disrupted cell walls, and the release of intracellular components [7] [8] [9]. These effects are attributed to oxidative stress and morphological changes rather than to direct cell lysis alone, demonstrating ozone's multifaceted antimicrobial capabilities.

This review highlights the advancements in ozone technology, emphasizing its applications in hand sanitizers and cosmetics, as well as the use of computational fluid dynamics (CFD) modelling. The CFD approach offers a detailed understanding of ozone mist behavior, enabling accurate predictions to enhance its safety and effectiveness in disinfectant applications.

# 2. APPLICATION OF OZONE IN HAND SANITIZERS AND COSMETICS

## 2.1 Hand Sanitizer

### *2.1.1. Introduction*

Ozone has emerged as a powerful oxidizing and antimicrobial agent, with various applications in decontamination. Among them are food, pharmaceuticals, textiles, drinking water, water treatment, and health care [2]. Ozone has been explored for its potential in disinfection and sanitation, offering a promising approach to combating the spread of viruses and other microorganisms. Moreover, the global COVID-19 pandemic has led to recent developments using different ozone-based technologies to enhance public health and safety [10]. Among the numerous applications, ozone-based hand sanitizers have emerged as a pivotal alternative to reduce COVID-19 transmission. While alcohol-based hand sanitizers and handwashing with soap and water are effective methods for hand hygiene, they have certain disadvantages. These conventional methods are usually associated with dryness and skin irritation, especially in individuals with sensitive skin [11]. In addition, there have been concerns regarding the flammability of hand sanitizers containing alcohol and the potential danger of toxic substances to children [12].

On the other hand, ozone, as a hand sanitizer, offers numerous advantages, including broad-spectrum disinfection, rapid efficacy, a chemical-free approach, mild on the skin, environmental sustainability, relatively low cost, and versatility. Ozone exhibits a broad range of antimicrobial activity, effectively targeting various bacteria, viruses, fungi, and other pathogens on the hands [10]. Moreover, ozone quickly neutralizes and eliminates microorganisms, providing rapid and efficient hand sanitation [2]. Skin dryness issues can be resolved through ozone-based hand sanitizer since it is less likely to cause skin dryness or irritation, promoting comfortable and frequent use [11]. In addition, this method is considered environmentally sustainable because ozonated water can be generated on-site, thereby minimizing transportation and reducing the environmental impact associated with the manufacture and disposal of conventional sanitizing products. The versatility of ozone-based hand sanitizers can be demonstrated across various settings, including healthcare facilities, educational institutions, public spaces, and food-processing industries. Finally, the production cost can be significantly reduced, especially for long-term operational expenses and resource utilization, without negatively impacting the environment or human health [13]. This section will discuss the application of ozonated water as a hand sanitizer and explore its effectiveness against various microorganisms, its cytotoxicity, its comparison with other disinfecting methods, and the associated challenges and prospects.

#### *2.1.2. Antimicrobial Action*

Hand sanitization is crucial for maintaining good hand hygiene, reducing the risk of infection, and preventing the spread of pathogens, including bacteria and viruses. Several studies have explored the potential of ozone-based hand sanitizers as a simple, cost-effective, and skin-friendly alternative to conventional alcohol-based hand disinfectants. Breidablik's group reported a slightly higher *E. coli* inactivation rate of an average of 98% (initial cell concentration >30,000 cfu/mL) using 0.4 ppm of ozonated water, compared to a 95% inactivation rate using an 85% alcohol-based sanitizer for a 30-second reaction time [11]. The test procedure was based on the European Standard EN 1500:2013, with slight modifications involving 30 nursing students. Additionally, 20% of participants reported adverse skin effects, such as burning or dryness, from alcohol-based disinfection. This study indicates that ozonated water can eradicate *E. coli* as efficiently as an 85% alcohol-based sanitizer, with no adverse skin effects. The same group conducted another study to compare the efficacy of alcohol-based sanitizer, ozonated water, and a combination of water and soap for hand sanitization [14]. The findings showed that soap washing was the most effective method, eliminating *E. coli* in 6 of 20 participants, with an average reduction in bacteria counts of 99.7%. In contrast, for alcohol hand rub and ozonated water, the average bacterial death rates were 92% and 98%, respectively, and followed a trend similar to that observed in the previous study. Although the WHO reports that properly formulated alcohol-based hand rubs (80–95% alcohol) typically achieve a 3.5 $\log_{10}$ reduction (99.97%) after 30 seconds, this study found a lower reduction of 92%, which is below the expected WHO efficacy range. This discrepancy may be attributed to factors such as variations in test conditions per EN 1500, the presence of organic matter, inadequate rubbing technique, or individual differences among participants, all of which can significantly reduce the real-world performance of alcohol hand rubs. Moreover, unlike alcohol-based sanitizer, participants responded positively to ozonated water, which did not cause any adverse skin effects. Notably, 33% of participants reported adverse skin effects, even in the absence of a prior history of dermatitis. These results indicate that ozonated water could be a viable alternative for hand hygiene.

In another study, Appelgrein et al. found ozonated water (4 ppm) to be less efficient than 60% propranolol-based hand rub against bacteria [15]. The alcohol-based hand rub had a 99.67% kill rate, compared with 93% for ozonated water. The discrepancy in the figures could be due to organic residues in the water, which can significantly reduce ozone levels. These ozone-consuming compounds may compete with microorganisms for ozone, hence limiting their efficacy [16]. Other factors, including pH and temperature, also affect ozone stability. Lower values of pH and temperature promote high solubility as well as stability of ozone [6] [17]. Additionally, Nakamura et al. reported comparable results between ozonated water (4 ppm) and antimicrobial soap and water, with both methods achieving a 3-$log_{10}$ CFU reduction. However, ozonated water was not significantly more effective than non-antimicrobial soap and water for hand washing [18]. Medium concentrations of ozonated water in the range of 4 ppm and below appear to produce an effect equivalent to, or slightly less effective than alcohol-based antimicrobial soap. Given this limitation, a higher concentration of ozonated water can be used, as it has stronger inactivating effects on microorganisms while causing mild or no skin damage during hand disinfection. Moreover, the production of high concentration ozonated water has become feasible with the development of electrolytic ozone generators [18].

Maintaining hand hygiene is an important measure for mitigating the transmission of transient microbial pathogens, particularly in the context of COVID-19. SARS-CoV-2 was reported to have a 9-hour survival time on human skin, thereby increasing the risk of viral entry into the body or its transmission from the skin to other surfaces [19]. Since viruses cannot repair oxidative damage, ozone is considered an effective agent for their inactivation, as proven in various studies, which include influenza, norovirus, and others [20]. For SARS-CoV-2, particularly, detailed studies have been conducted successfully in gaseous ozone [21] as well as in aqueous form [22]. Despite positive study results, the data reflected only the efficacy of ozonated water under batch conditions, in which the ozonated water was added to the test sample and rapidly degraded upon reaction with organic matter. To address this limitation, Lubitz et al. introduced a novel hand hygiene station called "Device" that was tested for its disinfection properties against SARS-CoV-2, which was affixed to a non-porous surface [23]. The device was designed to provide point-of-use antisepsis using ozonated water via a vortex-oscillation spray. The experimental setup was designed to simulate the actual application of this device for hand hygiene. The results showed that ozonated water (0.5 ppm) significantly reduced viral titer, with an average $log_{10}$ reduction of 4.33 CFU, when applied continuously for 7 seconds to the test sample. The impressive results indicate that freshly low-level ozonated water, when continuously supplied, significantly increases the viral killing rate within a very short period. Other studies [22, 24-25] which utilized the viral suspension method required contact times of 10 seconds to 1 minute for effective disinfection. These results are inherently challenging to interpret due to the short half-life of ozonated water and its ongoing degradation. Despite the positive results, this study is limited by the use of a proprietary spray device and by testing only glass surfaces. Further exploration of the Device using the standard test method (US EPA guidelines) for disinfectant products is warranted.

#### *2.1.3. Cytotoxicity Study*

With increasing interest in the use of ozonated water as a hand disinfectant, it is essential to understand its dermatologic safety clearly. Several studies have assessed the cytotoxic effects of ozonated water in mammalian cells. Kashiwazaki et al. reported no toxic effects of 4 ppm ozonated water on the normal-thickness stratum corneum of cultured epidermis after 15 min of exposure, compared with other hand disinfectants [26]. Furthermore, chemical-based hand disinfectants containing 1% chlorhexidine gluconate, 0.2% benzalkonium chloride, 83% ethanol, and 0.5% povidone-iodine were found to damage the stratum corneum. In another study, a human ear fibroblast (Hfib) cell line was used to assess the cytotoxicity of ozonated water [6]. The results show that the exposed cells maintained 100% viability across all tested ozone concentrations (0.4-0.8 ppm). These results suggest that a 1-minute exposure to ozonated water did not produce any cytotoxic effects. Moreover, Borges et al. observed no cytotoxic effects of ozone at concentrations up to 8 ppm on keratinocytes or fibroblasts, as demonstrated by MTT assay results [27]. Costanzo et al. tested cytotoxic effects on HeLa cells (a cervical cancer cell line) using 20 ppm ozone for a 10-minute reaction time [28]. After 24 and 48 hours, no significant cytotoxicity or apoptosis was observed in that cell line.

Numerous cases of adverse skin reactions associated with hand hygiene procedures have been reported, especially among healthcare professionals [29]. Among them, 85% of nurses are particularly at risk of hand dermatitis due to frequent hand-washing procedures and prolonged glove use [30]. Skin problems are classified into five groups: excessive dryness (96%), cracking (81%), redness (76%), itching (73%), and other conditions such as bleeding, contact dermatitis, or infection. Additionally, two eye surgeons observed improvements in their skin conditions after incorporating ozonated water into their preoperative hand hygiene routine [11]. Several findings support the potential of ozonated water as an alternative hand disinfectant, with minimal skin irritation relative to other agents.

#### *2.1.4. Challenges and Future Prospects*

The use of ozonated water as a hand disinfectant has attracted attention for its potential benefits, including environmental friendliness and minimal chemical residues. However, the integration of ozonated water into mainstream hand hygiene practices is not without its challenges. Ozonated water has a relatively short half-life, and maintaining its stability over time can be challenging, particularly during storage or when produced in large quantities. The use of additives such as citric acid, carbonate salts, and surfactants has been shown to improve the stability of ozonated water and prolong microbial inactivation [8, 31-32]. Moreover, the concept of ozone nanobubbles has been explored to enhance gas solubility, reflecting their stability and antimicrobial efficacy [33-35]. Additionally, implementing ozonated water systems may require specialized equipment and infrastructure, which could pose challenges for widespread adoption. Currently, various commercial ozone generators are widely available and capable of producing high concentrations of ozonated water. Continuous effort is underway to develop low-cost devices for this application [36-37]. The cost of ozone production has decreased substantially over the past two decades, enabling the development of new laboratory-scale devices and expanding their use in industrial applications [38]. Scaling up laboratory findings to larger systems must be done carefully. The choice between aqueous and gaseous ozone systems should be based on the intended application, and, in some cases, advanced automated technologies are incorporated to enhance operational efficiency and control [39]. Oliveira et al. [40] developed an ozonated-water spray chamber for rapid decontamination of PPE and evaluated its biocidal performance. Ozonated water (0.3–0.9 ppm) achieved more than a 2 $\log_{10}$ microbial reduction and up to 100% pathogen removal on PPE, while viral model tests demonstrated 99–99.9% inactivation of *Gammacoronavirus*. This technology has strong potential as a future tool to help prevent or effectively combat emerging pandemics by enabling rapid, efficient disinfection. Additionally, obtaining regulatory approvals for ozonated water as a hand disinfectant may be complex. The U.S. Food and Drug Administration (FDA) and the Environmental Protection Agency (EPA) have guidelines and regulations regarding the use of ozone as a disinfectant. Specific products or applications may require individual approvals or registrations, and manufacturers should comply with applicable policies and standards. Finally, building awareness and acceptance among the public and healthcare professionals regarding the effectiveness and safety of ozonated water as a hand disinfectant is crucial for its successful adoption. Analysis of perceptions of the use of disinfection technology using ozonated water achieved 92% approval among 106 participants [13]. A set of questionnaires was developed to assess the participants' perceptions of the new disinfection technology, their familiarity with ozonated water, and their understanding of its biocidal action. They also considered any discomfort experienced and their sense of safety.

The prospects of ozonated water as an effective disinfectant depend on advances in this technology. Ongoing research and development may yield improved formulations and methods for stabilizing ozonated water, thereby addressing its stability and shelf-life challenges. The biocidal mechanisms of ozone against fungi, protozoa, and parasitic organisms require further investigation, and studies should also explore the potential impact of antimicrobial resistance to ozone [2]. Moreover, viral inactivation kinetics are paramount, particularly those of SARS-CoV-2, given the current pandemic. This data would provide a better understanding of ozone antiviral action, enabling the development of more effective designs for ozone-contacting equipment [2]. As the effect of ozonated water is proven to be agnostic to SARS-CoV-2 variants, it would be attractive for ozonated water technology as a disinfecting agent alternative as the SARS-CoV-2 genome evolves [23]. Finally, its environmentally friendly nature aligns well with sustainability goals, making ozonated water a promising option for hand disinfection in healthcare facilities and beyond.

## 2.2. Cosmetics

### *2.2.1. Ozonated oil in the field of cosmetology*

Ozone therapy has become a significant method in cosmetology, garnering interest for its diverse effects on skin health and aesthetics. Ozone therapy encompasses various techniques, including subcutaneous ozone injection, rectal insufflation, and intravenous (IV) infusion. While all these methods aim to deliver ozone for therapeutic purposes, they differ significantly in their approach and application. Subcutaneous ozone injections, for instance, involve the direct infusion of ozone gas just beneath the skin, stimulating collagen production and refining skin texture. IV ozone therapy involves injecting medical-grade ozone gas directly into the bloodstream for rejuvenation. In contrast, rectal ozone insufflation introduces ozone gas into the rectum, aiding in detoxification, potentially enhancing skin appearance, and improving microcirculation and oxygenation, vital for skin health [41]. However, these approaches require careful administration to mitigate the risk of infection and ensure optimal outcomes since they may cause allergic reactions, and in rare cases, severe complications such as lung damage or neurological effects [42].

Therefore, one effective method of administering ozone is by utilizing ozonated vegetable oil. It involves the Criegee mechanism, in which ozone attacks the double bond of unsaturated fatty acids in the triglycerides of vegetable oils, forming various oxygenated products, such as ozonides, peroxides, and aldehydes [43]. Ozonated oil is more effective and has a higher safety profile compared to ozone therapy. For example, incorporating ozonated olive oil into cosmetic products such as facial packs and moisturizers can effectively hydrate the skin and address bacterial-related skin conditions, such as acne [42]. Studies have shown that ozonated oil exhibits antimicrobial activity, making it a promising candidate for topical use in cosmetic products to inhibit bacterial and fungal growth without damaging skin cells [44]. Several ozonated oils are accessible for topical application, with olive oil, sunflower oil, and coconut oil being commonly used in production. Despite numerous recent patents on vegetable oils, assessing their cost-effectiveness remains challenging. Examples of these oils include thyme, sesame, soybean, hemp seed, grape seed, jojoba, peanut, and rice bran [42, 45-46].

Ozonated vegetable oils serve as moisturizers and protectants and are particularly beneficial for individuals with compromised skin barriers. These oils are utilized in medicinal and cosmetic products, including ointments, gels, and sprays, for dermatological purposes such as treating skin infections, reducing exudation, and promoting wound healing. Previous studies have demonstrated the effectiveness of ozonated oils in healing severe skin lesions caused by bacteria like *S. aureus* and MRSA within 1–2 months, showcasing their efficacy, minimal side effects, and cost-effectiveness [47]. Research has also shown the antimicrobial activity of ozonated oils against various pathogens, including bacteria and protozoa, making them suitable for treating conditions like acne, herpes, psoriasis, fungal infections, and wounds [48].

#### *2.2.2. Methods of incorporating ozone into cosmetics*

Ozone can be directly incorporated into cosmetic formulations during manufacturing. This may involve bubbling ozone gas through the cosmetic mixture or exposing the formulation to ozone gas in a controlled environment. This controlled approach ensures that ozone dissolves properly, allowing cosmetic manufacturers to utilize its properties effectively. By adopting this technique, ozone becomes an element in enhancing skincare products [49]. However, ozone's reactivity may lead to instability in formulations, causing ingredient degradation and inconsistent product quality. Ozone also poses safety concerns due to potential irritation or harm to the skin, eyes, or respiratory system from ozone exposure during manufacturing or application in high concentrations [42].

Ozonated oils represent another aspect of the formulation. When ozone is combined with vegetable oil, it demonstrates potential beyond its qualities by promoting tissue regeneration and healing [50]. Adding ozonated oil to cosmetics involves incorporating vegetable oils treated with ozone gas into skincare or cosmetic products. Initially, high-quality oils, such as olive or sunflower oil, are exposed to ozone under controlled conditions. Oxygenated compounds formed during ozonolysis contribute to the antimicrobial and therapeutic properties of ozonated oils [43]. Ozonated oil is added to cosmetic formulations, such as creams, lotions, and shampoos, serving as a moisturizer, emollient, and antimicrobial agent. They act as carriers or active components in formulations, providing advantages such as cleansing, oxygenation of skin cells, regeneration, and a natural radiance boost [51]. This integration enhances product benefits, providing consumers with the potential advantages of ozone therapy in an easy-to-use format. Various beauty products, including moisturizers, serums, shower gels, body creams, emulgels, toothpaste, makeup removers, and lip balms, containing ozonated oil as an ingredient, are available for purchase in stores [42].

The inclusion of ozone in cosmetics offers several advantages. Its antioxidant properties confer potent protection against oxidative stress and environmental pollutants, thereby supporting skin health and vitality. Moreover, ozone facilitates enhanced penetration of other active ingredients into the skin, maximizing the efficacy of skincare formulations [6].

#### *2.2.3. Stability and shelf-life of ozonated cosmetic products*

Ozonated oils are generally more stable than free ozone because the oil matrix encapsulates ozone, allowing controlled release upon application and enhancing antimicrobial and healing properties. The stability of these oils depends on factors such as oil type, ozone concentration, and storage conditions [51], with lower temperatures and airtight packaging helping to prevent premature degradation and maintain quality and efficacy [52]. Oils with higher unsaturated fat content react more readily with ozone, resulting in a more stable ozonation process, whereas exposure to light, heat, and air accelerates degradation and reduces effectiveness [53]. To monitor stability during storage, Peroxide Value (PV) and viscosity are key indicators of chemical and structural changes. PV typically exhibits a two-phase trend, rising sharply in the early stages of storage before gradually declining as ozonides decompose. In contrast, viscosity increases steadily and correlates strongly with PV ($\rho > 0.74$), reflecting progressive structural changes within the oil matrix [54]. These parameters are susceptible to environmental conditions, as both PV and Ozone Efficiency decline more rapidly at elevated temperatures [55], highlighting the importance of low-temperature storage and the potential incorporation of stabilizing excipients to preserve shelf-life and therapeutic performance [55]

Direct infusion of ozone into cosmetic formulations poses significant stability challenges due to ozone's high reactivity, which can lead to the degradation of both the ozone and other ingredients, affecting the product's shelf life and performance [46, 51]. Furthermore, free ozone, which is not bound within a carrier like oil or a cosmetic formulation, is the least stable form due to its short half-life and rapid dissipation when exposed to air or in aqueous solutions, making it impractical for cosmetic applications [56]. Therefore, ozonated oils offer a more stable option for incorporating ozone into cosmetic products, providing a controlled release beneficial for skin treatment, while directly infused ozone demands careful handling and swift application [44].

#### *2.2.4. Research and development on ozonated vegetable oil*

Recent research on ozonated vegetable oils for cosmetic applications has focused on elucidating their potential benefits and optimizing formulation strategies. Ozonated oils have been reported to exhibit antimicrobial activity that can eliminate bacteria, fungi, and other pathogens, thereby sterilizing wounds and promoting healing. Radzimierska-Kazmierczak et al. reported that ozonated olive oil demonstrated notable anti-inflammatory and antimicrobial effects in skincare formulations, supporting its use for sensitive or irritated skin [51]. Kim et al. further showed that ozonated olive oil accelerates tissue regeneration with no observable skin irritation at the tested concentrations, indicating good *in vivo* tolerability [57]. Clinical evaluation of OLEOZON® for tinea pedis also confirmed effective antifungal activity without severe adverse reactions [58]. Additionally, a systematic review found that adverse effects associated with topical ozone-based formulations were infrequent and generally mild across 18 dermatological trials [59]. These findings are consistent with international safety frameworks, including the EU Cosmetics Regulation and ozone exposure limits such as OSHA's 0.1 ppm (8-h TWA) and U.S. EPA standards, thereby supporting the safe topical use of properly formulated ozonated oils.

Additionally, the antimicrobial activity of ozonated olive oil proved effective against a range of pathogens commonly associated with skin infections, highlighting its potential as a natural alternative to synthetic preservatives in cosmetic products [46]. Several ozonated vegetable oils, such as sunflower oil, are commercially available, as described in Table 1. The antibacterial activity of each product against various bacterial strains was evaluated to confirm its effectiveness and efficiency. For example, ozonated sunflower oil has a minimum inhibitory concentration (MIC) of 4.75–28.5 mg/ml against *S. aureus*, *E. coli*, *and P. aeruginosa.* Another example of an ozone-based product available on the market is Novox®, an extra virgin olive oil ozonated using innovative, patented methods. Novox® exhibits antiseptic properties for the treatment of various skin conditions, including skin lesions, oral ulcers, and wound dehiscence. Novox® was also tested to have a positive effect towards *S. aureus* and *Porphyromona gingivalis* with zone inhibition of up to 30.7 mm.

Table 1: Antimicrobial properties of the ozonated oil

| Product | Microbial Strain | MIC (mg/ml)/ inhibition zone (mm) | References |
|---|---|---|---|
| Bioperoxoil® (sunflower ozonated oil) | *C. albicans, C. parapsilosis, C. guilliermondii, C. tropicalis, T. asahii* | 11 – 19 mm | [60] |
| Microcapsules containing ozonized red pepper seed oil | *E. coli, P. aeruginosa,* methicillin resistant *S. aureus,* vancomycin resistant *E. faecium, C albicans* | 17 – 22.5 mm | [61] |
| Sunflower ozonated oil (different sources for ozone formation) | *S. aureus, E. coli, P. aeruginosa* | 4.75 – 28.5 mg/ml | [62] |
| Novox® (olive ozonated oil) | *S. aureus, P. gingivalis* | 19.0 – 30.7 mm | [63] |
| Sunflower ozonated oils with or without water, both "classical" and "high oleic." | *S. aureus, E. coli, S. uberis* | 5 - 40 mg/ml | [64] |
| Sunflower and flaxseed ozonated oils (with or without water) | *S. aureus, E. coli, P. aeruginosa, E. faecalis,* oxacillin resistant *S. aureus,* vancomycin resistant *E. faecalis* | 3 – 10 mg/ml | [65] |

#### *2.2.5. Challenges and Future Prospects*

The use of ozone in cosmetics presents promising antimicrobial properties but comes with significant challenges [44]. One significant hurdle lies in ensuring the stability of ozone within formulation until application, given its highly reactive nature and tendency for rapid decomposition [42]. Safety concerns also arise due to ozone's toxicity at high concentrations, requiring stringent precautions to prevent irritation or allergic reactions in consumers [66]. Preserving ozone's efficacy throughout the product's shelf life, along with the solubility of ozonated oil in water, further complicates compatibility with various cosmetic formulations. To address these issues, recent research has explored nano delivery systems, such as silica nanoparticles [67] and hyaluronic acid or chitosan-based nanocapsules [68], which improve aqueous stability, preserve antimicrobial activity, and enhance potential bioavailability. Despite these challenges, long-term stability, skin penetration, release kinetics, and comprehensive safety assessments remain limited, highlighting opportunities for further research before final cosmetic application. This includes efforts to stabilize ozone within formulations [69, 70], optimize delivery systems [67], and conduct comprehensive safety evaluations. Streamlined regulatory pathways and harmonization of international standards could facilitate broader commercialization and consumer acceptance of ozone-based cosmetic products.

## 3. COMPUTATIONAL FLUID DYNAMICS (CFD) MODELLING FOR IMPROVED OZONE TECHNOLOGY

### 3.1. Introduction

To effectively disinfect a variety of items and surfaces, it is crucial to have efficient circulation systems in place, especially in large-scale applications. Consequently, maintaining precise control over ozone concentration is a vital component of ozone technology, as it ensures successful disinfection. One way to measure ozone mist concentration is to hire a skilled individual (Hygiene Technician 1) to perform on-site air-quality monitoring [2]. Although it is the most accurate option, running this procedure can be costly, particularly for businesses and premises not subject to the Occupational Safety and Health (USECHH) Regulations 2000 [71]. Thus, CFD analysis is a practical approach for obtaining accurate measurements of ozone concentration at an affordable cost.

CFD is a subfield of computational mechanics, which is part of the larger category of simulation techniques [72]. Simulation is a valuable tool used by engineers and researchers to examine and understand engineering or physics problems under defined conditions. The selection of CFD as an investigation approach is driven by various considerations, such as utilizing CFD engineers to predict a product's performance without the need for physical prototyping [73]. This enables the detection of potential critical flaws that could be highly detrimental in real-world situations. Additionally, as mentioned previously, CFD can significantly decrease expenses associated with conducting experiments or analyses [74]. This is accomplished by eliminating factors such as material costs, equipment setup expenses, time, and other costly procedures.

In ozone technology, CFD plays a vital role in understanding and predicting ozone concentration behavior, which is crucial for the safe and practical application of ozone in various disinfection processes. The following section focuses on the valuable contribution of CFD as a robust simulation tool, enabling accurate predictions and improved understanding of ozone mist behavior.

### 3.2. Modelling Transport and Mixing

Understanding the behavior of ozonated mist or gas within a confined space relies heavily on accurately modeling transport and mixing, as ozone is naturally unevenly distributed. The concept of modelling transport and mixing involves considering how different air masses move within a specific space. This technique enables researchers to predict ozone diffusion and the development of localized regions with high or low concentrations. Theoretically, the ozone concentration decreases as its residence time increases [75]. Moreover, the theory was validated through experimental and numerical studies, which aimed to improve the understanding of ozone distribution in enclosed spaces [76]. A model room was constructed to experimentally investigate controlled airflow conditions, including laminar and turbulent flow, and the study considered theories of wall-surface deposition flux and ozone transport in indoor air. The decrease in ozone concentration observed in the stagnant region of the validated model room indicates ongoing chemical reactions that deplete ozone, as indicated by CFD analysis. This observation is consistent with the finding that concentration decreases along with ozone residence time.

An extensive study was conducted to examine the effectiveness of ozone in eliminating the coronavirus in coach trams [77]. The study aimed to provide experimental evidence of ozone's efficacy in inactivating the virus in public transportation systems. Additionally, a CFD simulation was developed to study the dispersion of ozone within a full-scale tram, accounting for both ozone self-decomposition and surface reactions, as shown in Fig. 1. The modelling framework incorporated Menter's SST k-ω turbulence model on a 1.76 million node mesh, gas-phase ozone self-decomposition kinetics, surface reaction boundary conditions to capture wall deposition and coupled flow and species transport with realistic ventilation patterns. Laboratory validation tests (100 ppm ozone, 95% relative humidity, 25 minutes exposure) demonstrated >99.8% viral inactivation on plastic surfaces. Field trials in an operational coach achieved 96-98% viral reduction, validating the CFD predictions. This study established that CFD can reliably predict ozone concentration distributions in large, enclosed spaces with complex geometries and ventilation systems, enabling design optimization for pathogen inactivation while minimizing occupant exposure risk. Employing a validated CFD model, they accurately determined the distribution of ozone mist concentration and consistently observed a decrease in ozone concentration with longer residence time.

Furthermore, factors including the formation, circulation, and degradation of ozone were analyzed by Jahromi et al. in their study [78]. Through their model, they successfully forecast ozone transport and mixing during disinfection and demonstrated a substantial improvement in understanding of this process. Using a comprehensive approach that addressed the entire modeling domain, they successfully predicted changes in ozone levels. The ozone persisted for an extra 2 minutes after being generated for 3 minutes. Furthermore, the research shows that even when the generator is paused for 5 minutes, ozone emission does not immediately cease; instead, it continues to spread throughout the room, as shown in Fig. 1. This work demonstrated that transient CFD is essential for cycle optimization, as steady-state approximations cannot capture the dynamic evolution of concentrations that are critical for efficacy and safety assessment. Validation against multi-point sensor data represents a rigorous approach applicable to any enclosed-space disinfection application. The valuable insights from this research can be used to optimize ozone distribution and effectively eliminate viruses in any environment. The combination of turbulence modelling and mixing is a powerful tool to analyze the behavior of ozone mist concentration in a confined area. By predicting ozone distribution and sensitivity to environmental factors, these models enhance disinfection strategies, ensure safety, and improve overall efficiency.

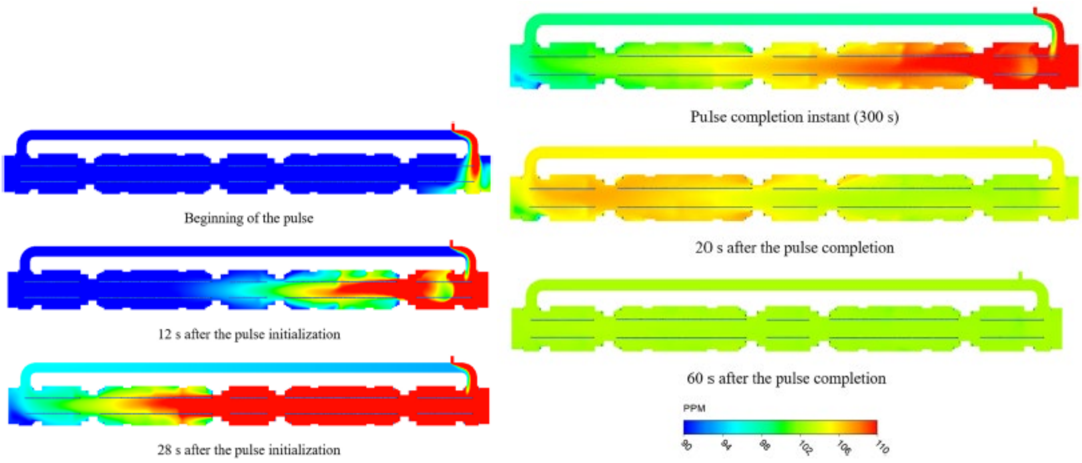


Fig. 1. Ozone mist distribution inside the simulation domain [77].

Unlike liquid-phase water treatment, gas-phase and mist applications require specialized multiphase modeling approaches to capture droplet transport, turbulent gas dispersion, evaporation, and surface deposition phenomena. Reynolds-Averaged Navier-Stokes (RANS) turbulence models are the practical standard for room- and chamber-scale ozone dispersion modeling owing to their computational efficiency. Validated applications include the standard k-ε model, Menter's SST k-ω model, and RNG k-ε and Realizable k-ε variants. Standard k-ε model which widely used for room ventilation and chamber flows; provides reasonable predictions of mean concentration fields [79] Menter's SST k-ω model demonstrated superior performance in the full-scale tram/coach study; better captures near-wall effects and recirculation zones whilst RNG k-ε and Realizable k-ε variants used in comparative studies; model selection affects early residence time behavior and short-circuiting prediction [80]. Comparative studies reveal that the choice of turbulence model significantly affects early-time concentration peaks during injection phases, the prediction of dead zones and recirculation regions, and residence time distribution (RTD) characteristics. During the validation stage, the best approach is to conduct a sensitivity analysis using at least two turbulence models (for example, standard k-ε and SST k-ω). The model that most closely matches the experimental tracer or sensor data should then be selected.

Conversely, Large Eddy Simulation (LES) offers higher fidelity by resolving large turbulent structures, improving predictions of transient concentration fluctuation, peak exposure levels in occupant breathing zones, and small-scale mixing and dead zone characterization [81]. However, LES requires substantially finer meshes and smaller time steps, increasing computational cost by 10-100 times compared to RANS. Therefore, LES is recommended for critical safety assessments requiring peak-concentration predictions, for fundamental studies to develop improved RANS closures, and for validating RANS predictions in complex geometries. Practical ozone dispersion applications typically use RANS for design and optimization, reserving LES for selected validation or critical assessment cases.

### 3.3. Designing Sampling Strategies

Developing a precise sampling strategy is vital to gain a thorough understanding of how ozone mist behaves during space disinfection. Sampling strategies, such as before-and-after ozone treatment, are used to evaluate the effectiveness of ozone disinfection across different areas. The microbial counts (bacteria and fungi) in a triage area are being investigated both before and after the application of ozone [82]. Samples were collected from both surfaces and the air within a designated area known to be at high risk of microbial contamination. In addition, a CFD simulation of a 3D model was conducted to simulate the distribution of ozone throughout the doctor's office. The use of both air and surface sampling methods provides a comprehensive insight into the relationship between ozone and microbial load. An ozone-based sanitation system was also used to enhance user safety by reducing the risk of bacterial and viral transmission via helmets. Recently, a novel sanitation system designed explicitly for helmets used in bike-sharing services [83]. Excessively slow airflow extends the ozone filling time. In contrast, higher air flow rates result in untreated areas due to increased internal turbulence. Using fluid-dynamic simulations, different ozone inlet rates were evaluated to determine the optimal setting for the generator. Using CFD simulations, the placement of ozone generators and ventilation strategies was optimized to achieve a more uniform distribution and enhance disinfection effectiveness.

Sampling strategy can also be used to refine disinfection protocols: if low ozone concentrations are detected in specific areas, the sanitization time can be extended; conversely, if high ozone concentrations are detected, the sanitization time can be reduced. CFD simulations can predict the time required for the ozone concentration to reach optimal levels and then decrease to safe levels. Schroer et al. conducted extensive research using CFD simulations to assess the dispersion of an ozone mist for sanitizing a hospital operating room [80]. Based on their simulation, ozone mist concentrations were higher on the walls near the generator, whereas they were lower on the farthest walls and on the ceiling. The average ozone mist concentration in the room was 11 mg/L, and a total of 10 minutes was sufficient to raise the concentration to above 4 mg/L, which is considered satisfactory for sanitizing the operating room surfaces. This validated study appears to be a valuable contribution to understanding the dispersion of ozone mist for hospital sanitization, particularly in the operating room. This study demonstrated that CFD can predict spatial and temporal ozone distributions in complex room geometries, thereby enabling the identification of dead zones and the optimization of generator placement and operating cycles. The coupling of experimentally validated decay kinetics with transient CFD simulations represents the best practice for ozonated mist modelling.

Understanding the behavior of ozone mist during disinfection is facilitated by a well-designed sampling strategy. By providing a comprehensive understanding of how ozone mist behaves, these strategies contribute to the safe and effective use of ozone disinfection across various settings.

### 3.4. Validation Methodologies for Gas-Phase and Mist Systems

Credible CFD predictions for ozonated mist and gas-phase applications demand systematic validation against experimental measurements. Recent studies outline robust protocols to ensure model reliability across flow, transport, and reaction phenomena. Multi-point, time-resolved ozone sensors at strategic locations within the modeled domain are the standard for validating temporal and spatial concentration mapping. Sensors target inlet regions for high concentrations, dead zones for low levels, occupant breathing zones for safety, and outlets for destruction efficiency. Data capture, generation, dwell, and destruction phases, with metrics including time to target concentration, peak values, decay rates, and spatial uniformity quantified by the coefficient of variation. Tamaddon Jahromi et al. validated transient simulations across a complete disinfection cycle using this approach, confirming accuracy in source terms, turbulent mixing, and decay models [78].

Chamber decay tests isolate ozone kinetics: inject ozone to a target concentration, seal the chamber, monitor decay, and fit exponential curves to determine the rate constant $k$. CFD simulates these with volumetric decay terms, tuning $k$ to match curves. Schroer et al. derived $k = 2.66\times10{-}4\ s^{-1}$ for ozonated mist and validated room-scale predictions [80]. Surface deposition tests with material-specific chambers yield deposition velocities for CFD boundary conditions, addressing removal in multi-material environments. Ultimate validation links CFD-predicted CT (concentration × time) distributions to lab-measured inactivation kinetics for target organisms. Surface-specific log reductions from bench tests are compared against field data using transient CT maps. Falcó et al. confirmed >99.8% viral inactivation in the lab (100 ppm, 95% RH, 25 min) aligned with 96-98% field reductions in a coach, validating the complete modeling chain from flow to biological outcomes. This approach establishes the gold standard for sanitization efficacy.

### 3.5. Challenges and Future Prospects

While CFD is not a direct measurement tool, it plays a valuable role in understanding and predicting the behavior of ozone mist**.** This information is crucial for researchers and engineers working with ozone mist in various applications. However, there remain challenges to overcome, as well as promising prospects for this research area. CFD models rely on assumptions regarding surface properties, ozone decay rates, and turbulence models. To accurately model these chemical reactions, one must possess extensive knowledge of reaction kinetics, species transport, and thermodynamic properties, which can be challenging to incorporate into CFD simulations [83-84]. In addition, it is vital to validate the accuracy of CFD simulations by cross-referencing them with real-world measurements of ozone concentration in various scenarios. This is crucial given the limited availability of experimental data and the variability in environmental conditions, which ultimately introduce uncertainties into the model's predictions. In addition, the complexity of airflow patterns in real spaces, especially those with irregular geometries or furnishings, poses a challenge for CFD models in accurately capturing them [85]. Finally, while CFD can simulate the movement and diffusion of ozone, it rarely accounts for the specific mechanisms by which ozone neutralizes viruses or bacteria. Integrating these chemical reactions into CFD simulations would result in more accurate predictions [16].

A major challenge in both current and future CFD applications is that the computational demands of simulations of ozone mist and gas dispersion can vary substantially with model fidelity, geometric complexity, and the coupling strategy employed. While precise CPU times and memory footprints depend on hardware, solver implementation, and specific geometry, systematic trade-offs between accuracy and computational cost fundamentally shape practical CFD applications in ozonated mist and gas technology.

Mesh density represents the primary driver of computational cost. For example, fine three-dimensional meshes are required to capture non-ideal flow effects in rooms, chambers, and vehicle cabins, and to resolve near-wall concentration gradients where ozone surface deposition and reaction are most critical [79-80]. Full-scale validated studies have employed meshes with 1.76 million cells to adequately capture recirculation zones and boundary-layer effects in a 28.6 m tram/coach geometry [78]. However, mesh refinement dramatically increases computational cost: doubling the grid resolution in three dimensions increases the cell count by a factor of eight, with corresponding increases in memory requirements and CPU time per iteration. Mesh sensitivity studies are therefore essential but costly. Careful mesh selection has been identified as critical to accuracy in room-scale ozone dispersion simulations. Yet, the literature lacks standardized guidelines for grid spacing in complex geometries with furniture, equipment, and ventilation systems. This absence of universal meshing protocols requires practitioners to conduct case-specific sensitivity analyses, thereby increasing the overall computational burden of a CFD study.

Furthermore, CFD simulations of ozonated mist and gas inherently rely on simplifying assumptions that prioritize computational tractability over comprehensive physical representation. Understanding these assumptions and their domains of validity is critical to the appropriate application of the model. Consider single-phase species-transport models that treat ozone as a passive or reactive scalar in the gas phase. They are computationally efficient and appropriate when ozone concentrations are diluted (<100 ppm), no droplet phase is present, and reaction kinetics are simple (e.g., first-order decay). However, for ozonated mist applications, discrete droplet tracking using Discrete Phase Model (DPM) Euler-Lagrangian approaches becomes necessary to capture polydisperse droplet transport, evaporation, and two-way momentum coupling with the carrier gas [79]. The study also demonstrated that conventional mixture models were inaccurate at low ozone concentrations in a sanitizing cabinet and switching to DPM or species transport significantly improved prediction fidelity. The choice of modeling framework (Species Transport for dilute gases, DPM for mist droplets, or a complete Eulerian multiphase model for dense sprays) depends on droplet loading, ozone concentration, and evaporation rate. It significantly affects both predicted concentration distributions and computational cost.

Despite the challenges, CFD studies of ozone mist have significant potential across numerous areas, offering promising prospects for the future. Further research can focus on enhancing understanding of ozone transport and mixing dynamics within indoor environments, considering factors such as room geometry, ventilation systems, and airflow patterns [76, 78]. This knowledge can be used to improve the accuracy of CFD models in predicting ozone dispersion and concentration gradients. Additionally, future research could focus on integrating ozone misting systems with Heating, Ventilation, and Air-Conditioning (HVAC) systems to enable precise, controlled ozone distribution. CFD simulations can help optimize HVAC configurations to enhance ozone dispersion and ensure uniform coverage throughout indoor spaces. Furthermore, beyond public transport and hospital facilities, CFD studies on ozone misting can be extended to other indoor environments such as schools, offices, shopping malls, and residential buildings. This expands the scope of research and provides valuable insights into the effectiveness of ozone-based disinfection strategies across various environments. Additionally, future research should continue to address health and safety concerns associated with ozone exposure, including potential respiratory irritation and long-term health effects. By optimizing ozone dispersion patterns and implementing appropriate ventilation strategies, CFD simulations can aid in evaluating and reducing exposure risks [77, 84]. Finally, ongoing research should also consider the sustainability and environmental impacts of ozone misting systems, including energy consumption, ozone generation methods, and byproduct formation. CFD simulations can aid in evaluating the ecological footprint of ozone-based disinfection technologies and identifying opportunities for improvement.

To address challenges and conduct future CFD studies, collaboration among researchers from disciplines such as fluid dynamics, chemistry, environmental engineering, and computer science is essential. Overcoming these challenges will improve the precision and reliability of CFD research on ozone misting, thereby facilitating the development of efficient strategies for managing indoor air quality. Exploring the potential of CFD studies on ozone misting offers promise for advancing our understanding of indoor air quality management and disinfection techniques, ultimately leading to safer, healthier indoor environments.

## 4. CONCLUSION

Ozone technology continues to demonstrate strong potential across hand hygiene, cosmetics, and CFD-supported process optimization. Ozonated water provides an effective and environmentally friendly alternative to alcohol-based sanitizers; however, challenges such as short half-life, stability, equipment requirements, and regulatory approval must be addressed. Future work should focus on improved stabilization strategies, viral inactivation kinetics, antimicrobial resistance, and the development of rapid-response disinfection systems for future pandemics. In cosmetics, ozonated oils offer valuable antimicrobial benefits but are limited by ozone's reactivity and instability. Emerging nano delivery systems show promise in enhancing stability, bioavailability, and formulation compatibility. Further research on long-term safety, optimized encapsulation, and regulatory harmonization is essential before large-scale commercialization. Moreover, CFD modelling has become a powerful tool for predicting ozone and mist distribution, yet its accuracy depends heavily on assumptions, model validation, and computational resources. Future advancements must integrate reaction kinetics, ozone–virus interactions, and mist-droplet dynamics, while expanding studies to real indoor environments and HVAC integrated systems. Cross-disciplinary collaboration will be key to improving model reliability and guiding safe, effective ozone-based disinfection strategies. Overall, ongoing innovations across formulation science, nanoengineering, and CFD modelling will drive the broader adoption of ozone technology, supporting sustainable, effective, and adaptable solutions for public health and environmental safety.

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