UNDERSTANDING HEAT IN COLD ATMOSPHERIC PLASMAS

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2 Context

Flexible endoscopes are widely used for diagnostic and therapeutic procedures in gastroenterology due to their non-invasive nature and clinical versatility. However, their complex internal architecture makes them highly susceptible to biofilm formation and microbial contamination [1], [2], [3]. Biofilms composed of polysaccharides, proteins, and DNA form a protective matrix that shields bacteria from external stresses, including detergents and disinfectants used in standard reprocessing protocols [2], [4]. This results in bacterial persistence and the risk of healthcare-associated infections (HAIs), with endoscopes being identified as the leading cause of such infections among reusable medical devices [5]. Conventional high-level disinfection (HLD) procedures, including manual cleaning followed by automated chemical disinfection and drying, fail to guarantee complete decontamination, particularly in the working channels of duodenoscopes and echoendoscopes [1], [6]. Up to 20% of reprocessed endoscopes remain contaminated despite adherence to protocols [7]. Moreover, aggressive chemical agents such as peracetic acid or high-concentration hydrogen peroxide (H_2O_2) are not suitable for repeated use due to material incompatibility and potential toxicity [8].

In response, **Cold Atmospheric Plasma (CAP)** has emerged as a promising alternative. CAP is a partially ionized gas operated at atmospheric pressure and near-ambient temperature, enabling the treatment of heat-sensitive devices such as endoscopes [9]. It generates a rich mixture of **reactive oxygen and nitrogen species (ROS/RNS)**, including OH radicals, ozone (O_3), NOx, hydrogen peroxide, and UV photons, which act synergistically to induce oxidative damage, DNA fragmentation, and membrane disruption in microorganisms [9], [10].

We demonstrated that CAP generated within the entire length of a PTFE tube under an Ar/H_2O flow enables effective biofilm eradication and bacterial inactivation [11]. Notably, bacterial regrowth was entirely suppressed after treatments as short as 5 minutes, and biofilm mass was reduced to $18 \pm 4\%$ after 30 minutes, even outperforming a 5-minute exposure to 30% liquid H_2O_2. The plasma discharge was designed to produce **short-lived OH radicals** directly at the contamination site, thus avoiding the loss of reactivity due to diffusion, a limitation observed in plasma jet systems [12], [13].

Interestingly, while CAP is described as non-thermal, a **moderate temperature increase** (~20 ± 2 °C at the tube wall) was recorded, which played a **secondary yet crucial role**. This heat facilitated the **evaporation of residual water** in the biofilm, exposing its structural components to further chemical attack. As we note, "complete biofilm removal requires vaporizing the water content to allow reactive species to degrade the non-volatile material" [11]. This finding aligns with earlier plasma-assisted decontamination studies, which also emphasized the synergy between thermal effects and reactive species in biofilm disruption [10], [14].

The CAP system proposed by us also addresses **environmental sustainability concerns** associated with the increasing use of disposable endoscopes, which can generate up to 40% more medical waste per procedure [15]. Given the healthcare sector's responsibility for up to 4.3% of global greenhouse gas emissions [16], developing **reusable and effective decontamination methods** becomes imperative, not only for infection control but also for long-term environmental viability.

This work lays the foundation for exploring CAP as a **standalone or complementary disinfection strategy**, aiming to shorten reprocessing times, enhance safety, and reduce environmental burden. It highlights the importance of producing reactive species in direct contact with contaminants and sheds light on the **mechanistic interplay** between oxidation, UV-induced damage, electrical disruption, and mild heating in CAP-based sterilization of medical devices.

3 Work

While Cold Atmospheric Plasma (CAP) is widely recognized for its chemical reactivity and low-temperature operation, **localized heat generation within the discharge, particularly in filamentary structures, remains poorly understood**. In the context of endoscope decontamination, recent studies, as mentioned earlier, suggest that **moderate heating may contribute to biofilm removal** by promoting water evaporation and enhancing the action of reactive species. However, the **extent and influence of these thermal effects,** often considered secondary, have not been systematically characterized.

This master thesis focuses on the **physics of heat generation in CAP**, particularly in confined geometries mimicking endoscope lumens. The objective is to better understand **where, how, and to what degree heat is produced and distributed**, and whether this contributes significantly to microbial inactivation and biofilm detachment.

Specifically, the work will:
- Analyze the **thermal behavior of filamentary plasma discharges** in PTFE tubing (3 mm diameter), using thermal diagnostics (e.g., IR imaging, thermocouples) and plasma spectroscopy.
- Correlate observed temperature rises with **plasma parameters** (gas composition, power, etc.) and (maybe) **biofilm removal efficiency**.
- Evaluate the **relative impact of heat** compared to reactive species in the overall decontamination process.
- Explore **optimization strategies** that enhance beneficial thermal effects without compromising the non-destructive nature of CAP.

Through this investigation, the master thesis aims to clarify the **often-underestimated role of heat** in cold plasma disinfection and to inform the **design of more effective and energy-efficient CAP systems** for medical applications.

4 References

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