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Accurate quantification of plasma effects – plasma dose – on a substrate is challenging due to lack of direct measurements of plasma effects. This challenge is further aggravated by the presence of multitude of different effects (i.e., thermal, chemical, and electrical) and their synergistic interactions. Although plasma dose quantification is highly specialized in different applications, dose metrics share some commonalities: (i) they should describe the cumulative, non-retractable nature of a plasma treatment, and (ii) they should be defined in terms of a measurable property of a target substrate, which is related to some characteristics of underlying chemical/thermal/electrical processes on the substrate such as volumetric energy absorbed as ionizing radiation, or total thermal accumulation.

During the first year of the project, we demonstrated the usefulness of model-based feedback control for mitigating the effects of variabilities and disturbances on operation of atmospheric pressure plasma jets (APPJs), which is a widely used plasma discharge at atmospheric pressure. In the second year of the project, we addressed the problem of spatially uniform delivery of thermal effects of a kHz-excited APPJ in helium on a dielectric substrate. To this end, we developed and experimentally implemented a hierarchical, feedback control strategy for real-time regulation of thermal dose delivery. The control strategy consists of: (i) a proportional-integral (PI) controller that regulates the maximum substrate temperature at the APPJ centerline via manipulating the applied peak-to-peak voltage at fast sampling frequency (~ 1 s), and (ii) an optimization-based supervisory controller that plans the thermal dose delivery every 6 s via determining the optimal values for the reference maximum substrate temperature in the PI controller based on the user-specified treatment time and the reference thermal dose within the treatment area.

Here, we discuss a sample result of this study; further details can be found in the manuscript "Spatial Thermal Dose Delivery in Atmospheric Pressure Plasm Jets" that is submitted to the Journal of Plasma Sources Science and Technology. Figure 1 shows the spatial thermal dose delivered at the end of the treatment time 5 min, the maximum temperature profile T_{max} (measured output), and the applied voltage profile V_{p2p} (input) for the cases of: (a) no feedback control and thermal dose delivery planning, (b) the open-loop dose delivery planning strategy, and (c) the closed-loop dose delivery planning strategy. As can be seen in Figure 1a, T_{max} exhibits high variability and sensitivity to the APPJ operation when no feedback control is used for regulating T_{max}. The inability to plan the dose delivery in this case, along with the variabilities in T_{max}, leads to significant non-uniformity in the spatial dose delivery along the target region. For example, the thermal dose delivered at x=-5 mm is significantly lower than the desired thermal dose reference (i.e., $CEM^{ref}_{T}(5,x)$=1 min), whereas at x=5 mm the delivered thermal dose is approximately twice the reference. Thus, the results suggest that the effectiveness of thermal dose delivery can be severely compromised in the case of no feedback control and thermal dose delivery planning. Figure 1b shows the results obtained using the open-loop dose delivery planning strategy, where the reference of the PI controller is determined by solving the optimization problem once, offline. As expected, the PI controller can effectively track the offline-computed reference profile for the maximum substrate temperature, T_{max}, while mitigating the variabilities that stem from the APPJ translation and possibly other unknown sources of disturbances. Yet, even though a significantly more uniform thermal dose is achieved relative to the case of no feedback control, there is an offset between the delivered thermal dose and the reference dose. This can be attributed to the discrepancy between the planned dose and the actual thermal dose delivered due to the fact that the temperature reference profile is determined offline and thus it is blind to the actual state of dose delivery during the plasma treatment. On the other hand, the closed-loop dose delivery planning strategy mitigates this discrepancy via real-time solution of the optimization problem. In this case, the actual thermal dose delivered to the substrate is inferred from temperature measurements every 6 s and is fed back to the supervisory controller. This allows online computation of the reference temperature sent to the PI controller. Figure 1c suggests that the closed-loop dose delivery planning enables achieving a close to uniform thermal delivery along the target region at the end of the treatment time, while maintaining high reproducibility and low variability in the dose delivery. In our future work, we will investigate the effectiveness of optimization-based feedback control for uniform thermal dose delivery on two-dimensional surfaces with nonuniform chemical, electrical, and thermal characteristics.

Impact of the research: The PI had no background in the field of cold atmospheric plasmas and their wide range of applications in materials processing and reaction engineering prior to the start of this project. This grant was his first funding in this area, which enabled him to initiate a new research direction with the focus on advanced control of plasmas toward reproducible and effective plasma treatments at atmospheric pressure. Our research group has pioneered the research on model-based control of the atmospheric pressure plasma systems. This grant has been used to fund one graduate student, who performed multidisciplinary research at the interface of plasma and systems and control. This project has led to one journal publication, and a second manuscript that is currently under review.

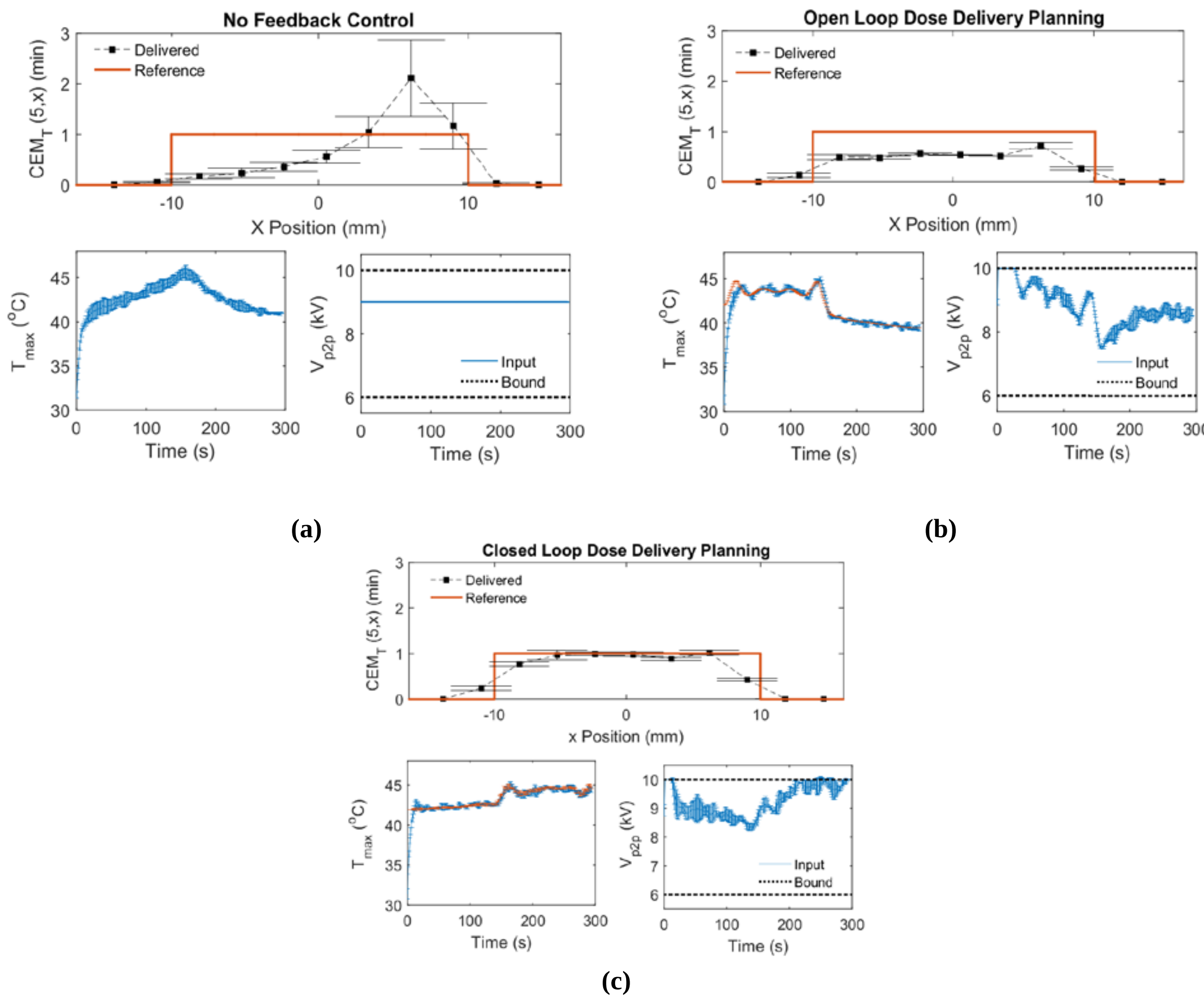

Figure 1: Delivered thermal dose $CEM_T(5,x)$ along the treatment region [-10, 10 mm], maximum substrate temperature T_{max}, and applied peak-to-peak voltage V_{p2p} for: (a) no feedback control and dose delivery planning, (b) the open-loop dose delivery planning strategy, and (c) the closed-loop dose delivery planning strategy. The error bars show the standard deviation of variables based on three replicate runs.