Measurement and Simulation of a VHF Remote Plasma Source

Created by

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Abstract

Remote plasma sources are commonly used for chamber cleaning, blanket stripping, downstream abatement, and ashing processes. Most of the current remote sources are designed to operate at very high plasma densities using microwave or inductively-coupled RF energy. Often, these systems are highly tailored for specific applications, and due to the coupling mechanism or chemical incompatibility, the operating ranges are limited. This paper describes a new remote source technology using capacitively coupled, VHF energy to produce a flexible and unique remote plasma generator. The electrode design and internal construction are compatible with most processing chemistries, and allow generation of very low to very high plasma densities across extensive flow and pressure regimes. Due to the expansive operating range and chemical compatibility of the new, VHF RPS, characterization of the device becomes challenging. Engineering simulation methods are being used to supplement laboratory experimentation. Mechanical simulation has been employed to model and optimize aspects of the VHF RPS design, including: process gas flow, thermal performance, and structural reliability. Currently, plasma simulation is also being investigated as a method to augment and enhance characterization of the VHF

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RPS. Preliminary plasma simulation results are presented and compared to empirical data for a benchmark operating condition. Future work as well as long-term goals for plasma simulation are discussed.

Background

The term "remote plasma source" (RPS) describes a plasmagenerating device (source) which is installed remotely from the process chamber. By separating the higher energy plasma discharge (and the externally applied electric field) from the processing chamber, a remote plasma source can introduce a desirable stream of radicals to the substrate surface while minimizing bombardment of the substrate – and the associated damage – from higher energy ions and photons which are prevalent in the active discharge [1].

The archetypal RPS is an inductively coupled plasma (ICP) chamber, often toroidal in design. Conventional applications for remote plasma sources include: chamber clean, process chamber exhaust abatement, stripping, or ashing processes. However, the application space for remote plasma generation is expanding. In recent years, RPS technologies are being considered – and demonstrating advantage – in a wider scope of applications, such as: radical generation for direct processing, low energy processing, and augmentation or replacement of in-situ sources [1].

Existing remote source technologies, (toroidal ICP, for instance) have relatively narrow operating ranges and are often designed for – or limited to – specific applications. Having a confined, determinate operating space can be advantageous, in that characterization and optimization of the remote plasma source device becomes more straightforward. The disadvantages, however, are realized when developing or optimizing processes outside the original design space; in this situation, a more capable RPS device with an expanded operating range would offer numerous benefits by enabling: optimization of operating pressure, both in the remote source and in the downstream chamber; experimentation with different feedstock chemistry; expanded flow rate, and residence time capability; and ignition and operational stability across a wider range of power levels, including pulsed power.

A novel, remote plasma source has been designed, using a capacitively coupled plasma (CCP) technology driven by very high frequency (VHF), 60 MHz, input power. This new RPS has demonstrated operating range versatility not seen in existing, comparable remote source devices. Initial characterization of this VHF CCP remote source has been previously published [1].

Empirical Characterization

A common challenge with remote plasma sources is sustaining a high-density stream of energized ions, radicals, and/or neutrals as far downstream as the substrate. In a typical RPS device, the plasma discharge is almost exclusively contained within the source itself. As soon as energized particles leave the source, the densities of process-useful constituents begin to diminish due to surface and volume recombination within manifolds and connecting tubulature [1]. The VHF RPS, on the other hand, has demonstrated an efficacy to project highdensity, active plasma significantly beyond the exit throat of the device: a distinguishing ability of this device and potentially a great advantage compared to a typical remote plasma source (Figures 1, 2) [1].

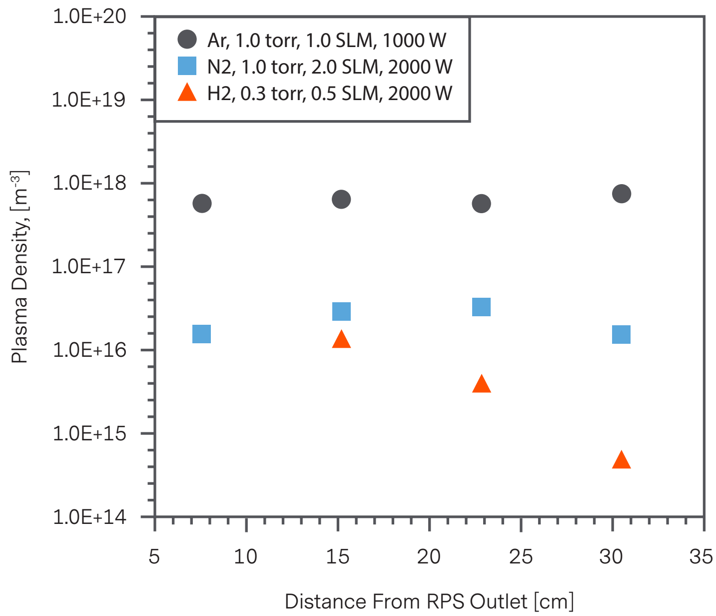

Figure 1. Langmuir probe data showing a sustained, high level of plasma density projected outside the source, into down-stream tubulature, for various chemistries [1].

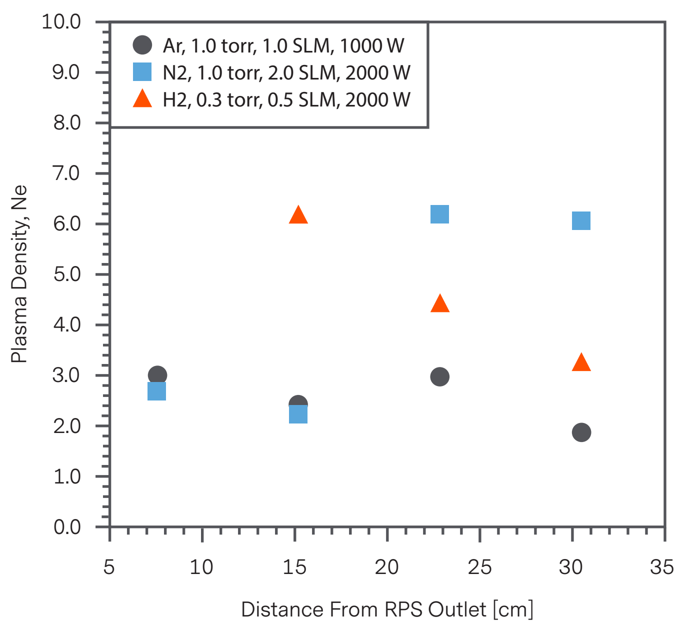

Figure 2. Corresponding electron temperature values for the points in Figure 1. Te is also maintained fairly constant downstream from the RPS [1].

Performance of the VHF RPS has been measured using methods and devices typical for plasma processes: Langmuir probe, optical emissions spectroscopy (OES), and a retarding field energy analyzer (RFEA) sensor [1]. Additionally, some nontraditional methods of empirical characterization have been employed, such as calorimetry and high-speed thermography [2].

Measuring and experimentally characterizing the operating performance of the VHF RPS is a circuitous exercise; not only is the plasma projection phenomenon dependent upon multiple process parameters, but the VHF RPS is also capable of an expansive operating range. To augment empirical data and to analyze operational attributes not easily measured in the lab, engineering simulation and modeling methods have been employed. To this point, the focus has primarily been on mechanical simulation.

Mechanical Simulation

Throughout the design process of the VHF RPS, mechanical simulation has been used to effectively predict the performance and reliability of the device [2]. Computational fluid dynamics (CFD) is employed to model and optimize critical aspects of the VHF RPS design, including: neutral (bulk) gas residence time, gas diffusion and injection symmetry, and water cooling of the chamber walls (Figure 3). Furthermore, multi-physics simulation methods have been used to assess the thermal performance and structural integrity of the design. For example, the primary electrode in the VHF RPS is a multi-layer, multi-material assembly which absorbs heat on the plasma-exposed surfaces and transfers the heat through the layers and into a water-cooled internal device. CFD models are coupled with nonlinear finite-element analysis (FEA) thermal and structural models, and the systems are solved simultaneously to predict the resulting thermal-mechanical strains and associated structural response during operation [2].

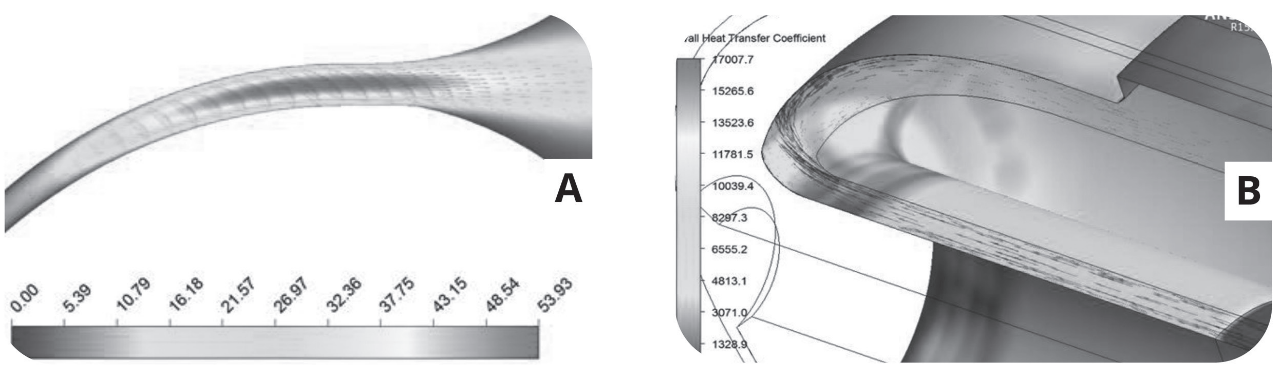

Figure 3. CFD has been used extensively to model and optimize both fluid and thermal aspects of the RPS design.

A successful mechanical analysis is predicated by an accurate, correlated model of power deposition (heat flux) into the walls of the RPS – a function of plasma position. As stated previously, the position of plasma within the remote source and downstream tubulature is dynamic, dependent on both the geometry of the apparatus as well as the process parameters. Mechanical analysis can be used to optimize the performance or reliability of a component in the system, but if that component affects the plasma power deposition, then the wall heat flux needs to be re-characterized for every design iteration. Currently, the only means of characterizing the wall heat flux is through laboratory experimentation – a process which is impractical for the entire, expansive operating range of the VHF RPS. In lieu of an exhaustive, empirical characterization, the simulation techniques currently in use can be expanded to also solve for the plasma physics. Accurate, analytical predictions of the plasma response within the remote source would significantly increase the thoroughness and efficiency of both characterization and optimization of the VHF RPS.

Plasma Simulation

Background

Although very complex and often intimidating, plasma simulation is starting to become a mainstay in both industry and academia [3]. In order to model the plasma behavior within a non-equilibrium discharge, multi-physics code is used to simultaneously solve for the electromagnetics, fluid flow, heat transfer, species chemistry and transport equations. There are some commercially available software packages which allow for plasma simulation. The simulation software chosen for the VHF RPS project, CFD-ACE+®, has an extensive list of capabilities and advantages, including: the ability to model both 2D and 3D geometry; offline Boltzman solver for increased electron energy distribution function (EEDF) relevancy; capabilities for both statistical mechanics (low pressure, high Knudsen number conditions) and continuum mechanics (high pressure, low Knudsen number conditions) fluid regimes; a comprehensive material library, as well as a database of surface and volume chemistry reactions and crosssections; the ability to couple reactor-scale simulation results to feature-scale, topographic simulations; and a capability for both inductively coupled plasma (ICP) as well as capacitively coupled plasma (CCP) simulations [4].

The capability to simulate plasma provides many benefits to the VHF RPS. Because of the device’s expansive operating range, plasma simulation may facilitate characterization of plasma behavior for operating conditions that aren’t feasible in the laboratory. Furthermore, the ability to optimize the design analytically will significantly reduce the number of design iterations, which is especially important for the long lead-time components in the design. Lastly, plasma simulation can be used to characterize the delivery of plasma and plasma bi-products downstream of the RPS, assisting process optimization in the field.

Simulation Approach & Verification

The VHF RPS is a CCP type reactor, but beyond the capacitive coupling nature of the device, there are very few similarities to other, commercial CCP reactors. The typical CCP chamber features parallel, flat plates with a consistent spacing (gap) between the electrodes, and therefore a near-symmetric electric field. In contrast, the VHF RPS has curvilinear, 3-dimensional electrode surfaces with variable electrode spacing and an asymmetric electric field. Additionally, the VHF RPS operates at 60 MHz, a higher frequency than the typical CCP reactor (13.56 MHz). CFD-ACE+® has demonstrated the ability to accurately simulate plasma within a typical CCP arrangement [5-7]. For the VHF RPS, however, the aforementioned idiosyncrasies of the device demand a more deliberate approach to plasma simulation.

To test and prove the CFD-ACE+® code, a benchmark case was chosen based on the following criteria: relatively simple chemistry, operating parameters that are achievable in the laboratory, and power and pressure values that are typical for CCP reactors. The chosen case is Argon at 1 torr, 1 SLM flow, and 1000 watts input power.

Any engineering simulation needs to be vetted against empirical results before the models can be used with confidence. It is not currently feasible to probe the plasma parameters within the VHF RPS, due to probe overheating and geometrical challenges. However, Langmuir probe data collected from the RPS outlet and down-stream tubulature can be used to check and correlate the simulation [1]. The primary goal for the VHF RPS benchmark case is for the simulation to approximate experimental data (within 20 %) for the parameters of electron temperature (Te) and plasma density (Ne), in the down-stream tubulature, at multiple distances from the outlet of the RPS (Figures 1, 2).

Downstream plasma parameters are certainly important for remote plasma source applications, but there is also an interest in understanding the plasma within the RPS. In this case, the chamber wall heat flux data collected via thermography can be compared to the computed power deposition from the model to check the simulation against empirical measurements. Furthermore, the distribution of power dissipation to the various chamber walls in the simulation can be compared against calorimetry data from laboratory experiments.

Model Setup

For the most part, the VHF RPS can be considered axisymmetric. It is assumed that a 2-dimensional (2D), axisymmetric representation will be sufficient for the purpose of modeling the bulk plasma behavior. The 2D model of the VHF RPS consists of two types of surface bodies: a fluid body representing the vacuum chamber, and multiple solid bodies representing the chamber walls. The surface bodies are meshed using a structured grid of quadrilateral elements. The grid spacing is significantly finer in the vacuum body, near the walls, to fully resolve the plasma sheath characteristic of CCP discharges.

The fluid is represented by the Argon gas model in the CFDACE+ ® materials database. The benchmark case at 1 torr presents a fluid regime where the continuum assumption is valid, so the ideal gas law and bulk transport properties for Ar apply. The solid bodies comprising the chamber walls are a dielectric material. The material model for these bodies is based on temperature-dependent thermal and electrical properties. Volume and surface chemistry reactions are solved for according to the reactions defined for the Argon model in the CFD-ACE+® materials database. The electrodes of the VHF RPS are represented by the boundaries (line bodies) comprising the non-plasma-exposed walls of the chamber. A constant input power of 1000 watts is applied to the powered electrode, with an alternating current at 60 MHz, and the simulation code calculates the resulting voltage between the electrodes. The non-powered electrode is held at a reference potential of 0 volts.

The CFD-ACE+® software handles CCP plasmas in a transient manner, with a fine, inner convergence loop for the CCP variables, and an outer, coarser convergence loop (~103 larger time steps) for the non-CCP variables (fluid flow, neutrals, heat transfer) [4]. During the transient solution, a number of parameters are monitored in order to gauge the convergence trajectory and status, namely: plasma density, electron temperature, and plasma potential.

Current Results

As expected, the unique characteristics of the VHF RPS have indeed proved nontrivial for simulation. Despite the challenges, significant progress has been made towards replicating the benchmark empirical data. At the time of writing, the simulation had yet to fully convergence, but the convergence trajectory appears typical and on course (Figure 4). There are some stability improvements being implemented into the solver algorithms which are expected to facilitate full convergence of the model in the near future. Because the solution has not fully converged, it is not relevant to compare variable magnitudes yet. However, it is interesting to begin analyzing the gradients and trends that exist at the interim solution point.

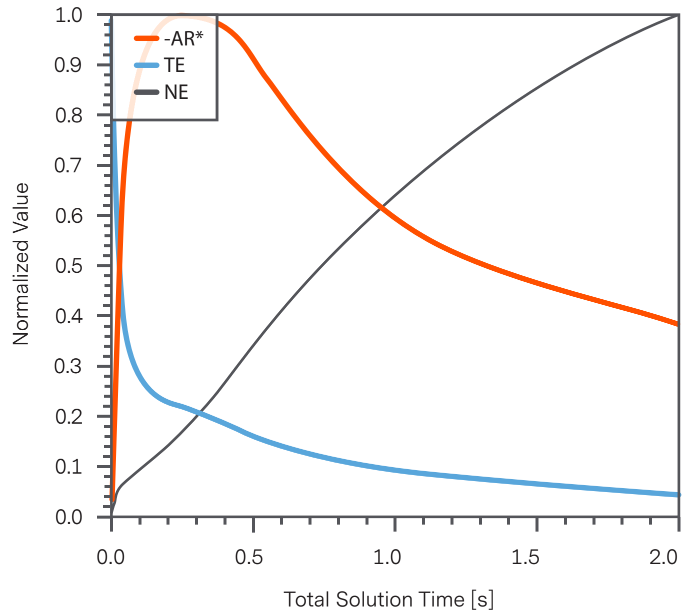

Figure 4. Key plasma parameter values (normalized) during the transient, time-stepping solution. The variables have not yet reached steady-state values.

The position of plasma (density gradients) within the RPS, and the associated power deposition, agree very well with the distribution of wall heat flux as measured by thermography (Figure 5). When the solution is fully converged, it will be possible to calculate the model-predicted wall heat flux and the associated temperature of the chamber walls and compare these results directly with the infrared temperature measurements. Preliminarily, it appears the simulation is accurately capturing the gradients of density and power deposition within the active discharge.

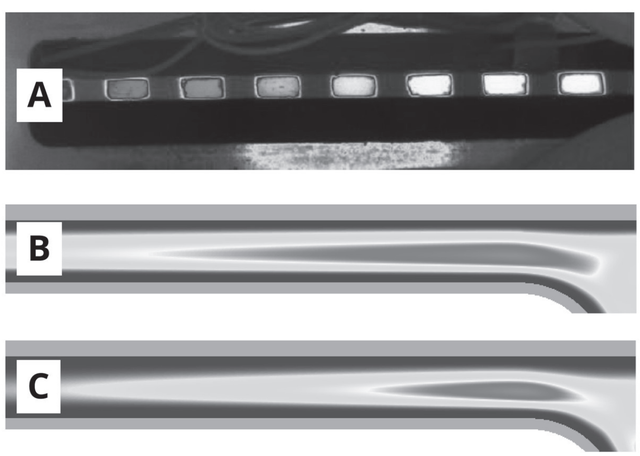

Figure 5. Contour plots showing the VHF RPS outer wall temperature, as measured by infrared thermography (A), the simulation-predicted plasma density (B), and the simulation-predicted plasma power deposition (C). Simulation results are preliminary and only partially converged.

Due to the intended application of a remote source, the characteristics of the plasma and plasma bi-products projected from the RPS are of keen interest. As mentioned previously, one of the goals of the benchmark simulation is to correlate downstream plasma data with empirical measurements. In the current, non-converged solution, there are some discrepancies in the downstream plasma parameters. The simulation exhibits a decline in plasma density in the outlet tube, while the Langmuir probe data for the same operating condition shows a stable plasma density through the output tube. The transient nature of the CCP simulation, and the fact that the solution has not fully converged (i.e. reached steady state) may account for the disparity in plasma density gradients (as well as the magnitudes) within the outlet tube; in other words, the total transient time at the interim solution point may not be sufficient to allow the bulk plasma to fully envelop the downstream tubulature. More solution iterations or experimentation with time stepping is necessary to fully understand this phenomenon.

Future Work

It is expected that the on-going enhancements to the CFDACE+ ® code will facilitate a fully converged solution in the near future. At that time, the next step will be to experiment with and understand the significance of various plasma and solver options, including: ion momentum effects, electromagnetic wave effects in the CCP discharge, external circuit coupling, solving for electron stochastic heating, and using an offline Boltzman lookup table to compute more relevant electron energy distribution functions. Also, some work will be done to increase the computational efficiency of the solution, enabling faster – yet still accurate – future modeling of other geometry and process variations.

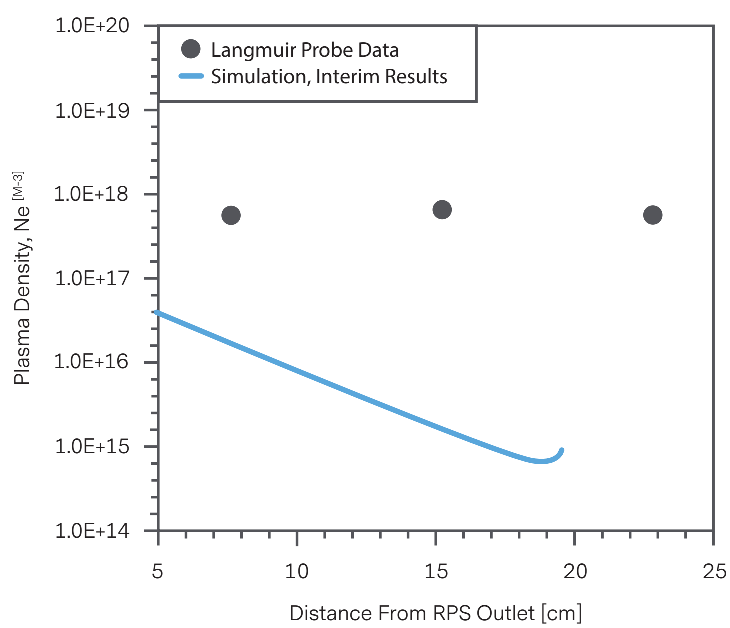

Figure 6. Plasma (electron) density projected outside the VHF RPS, into downstream tubulature. The partially-converged solution data is compared to experimental data collected via Langmuir probe.

One of the more unique aspects of the VHF RPS is its compatibility with a very broad range of chemistries, and therefore one of the most logical simulation goals will be to correlate and simulate the plasma response – particularly the downstream characteristics – for process gasses other than Argon. After the benchmark case is fully vetted, simulation will be used to explore Hydrogen, Nitrogen, NF_3, and other plasmas.

Finally, a longer-term goal will be to simulate the delivery of plasma bi-products (neutrals and radicals) into downstream chambers – the characteristic function of a remote source.

Conclusions

The enhanced versatility and novel design of the VHF RPS make it impractical to fully characterize using only empirical methods. Engineering simulation methods have been used with great success to predict and enhance the mechanical performance of the RPS through the early design phases. Preliminary efforts using simulation to characterize the plasma behavior are producing promising results. The plasma density and power deposition gradients within the RPS agree well with empirical measurements. The magnitudes of plasma parameters do not yet match experimental data, but the solution has not yet reached full convergence. It is expected that a fully converged solution will be reached soon, aided by enhancements to the commercial plasma simulation software, CFD-ACE+®, which are currently being tested. Once the benchmark simulation case has reached a solution and has been fully vetted to empirical data, future work will include simulation of different gas chemistries, pressures, and power levels. The long-term goal is to use simulation to accurately predict the delivery of plasma and plasma bi-products into downstream processing chambers.

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