Simultaneous real time control of O and F radicals in an argon/oxygen/fluorocarbon plasma

B. J. Keville and M. M. Turner

National Centre for Plasma Science and Technology
School of Physical Sciences
Dublin City University Glasnevin, Dublin 9, Ireland

1. Plasma process control simulation

Figure 1. is a schematic of closed loop control of a plasma process simulation. The $Ar/O_2/C_4F_8$ global model is adapted from the chemistry sets contained in [1], [4] and [7]. Each mass flow controller (MFC) is modelled as a first order linear transfer function, which has been determined from the step response of a commercial MFC. The relationship between the forward power P_{for} and the power P deposited in the plasma is modelled using an impedance model and a matching circuit. Transport delays, which have a destabilising effect on control loops, should be included in any simulation. Given (simulated) measurements from the plasma, the controller is required to adjust the flow rate set points $F^{\star}_{O2}$ and $F^{\star}_{C4F8}$ in order to maintain n_O and n_F at the set points $n^{\star}_O$ and $n^{\star}_F$, respectively, despite the effects of process disturbances.

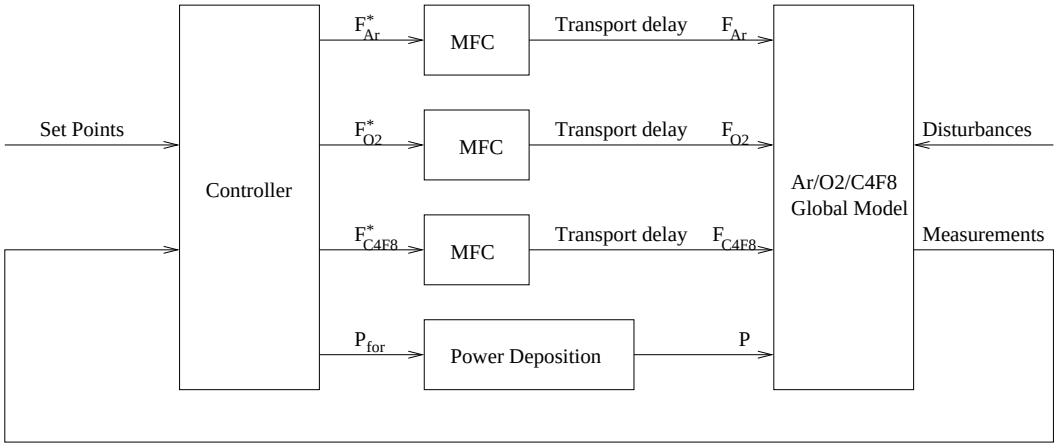


Figure 1. Plasma process control simulation

2. The transfer function for atomic oxygen density

The relationship between F_{O2} and n_O may be approximated by the linear transfer function

$$\frac{n_O(s)}{F_{O2}(s)} \approx \frac{K_O}{s\tau_{res}+1}, \tag{1}$$

where τ_{res} is the residence time and K_O is the process gain. The relationship between F_{O2} and $F^{\star}_{O2}$, may be expressed in the form

$$\frac{F_{O2}(s)}{F^{\star}_{O2}(s)} = \frac{e^{-s\theta_m}}{s\tau_m+1}, \tag{2}$$

where τ_m is the characteristic rise time of the MFC and θ_m is a transport delay. Equations (1) and (2) yield the process model

$$G_O(s) = \frac{n_O(s)}{F^{\star}_{O2}(s)} = \frac{K_O e^{-s\theta_m}}{(s\tau_m+1)(s\tau_{res}+1)}. \tag{3}$$

3. Closed loop control of atomic oxygen

G_O defines a second order plus dead time process, which may controlled very effectively with a Proportional-Integral-Derivative (PID) controller, the transfer function of which may be expressed in the form

$$G_c(s) = K_c\Big(1+\frac{1}{\tau_I s}+\tau_D s\Big), \tag{4}$$

where K_c is the controller gain, and τ_I and τ_D are the integration and differentiation time constants, respectively. The Direct Synthesis PID settings are [5]

$$K_c = \frac{1}{K_O}\frac{\tau_m+\tau_{res}}{\tau_c+\theta_m}, \tag{5}$$

and

$$\tau_I = \tau_m+\tau_{res}, \tau_D = \frac{\tau_m\tau_{res}}{\tau_m+\tau_{res}}, \tag{6}$$

where τ_c is the rise time of the desired closed loop transfer function. With τ_I and τ_D given by (6), it may be shown using the Nyquist stability criterion that the closed loop transfer function is stable if and only if $0 \le K_c < K_u$, where

$$K_u = \frac{1}{K_O}\frac{\pi(\tau_{res}+\tau_m)}{2\theta_m}. \tag{7}$$

The gain margin, $GM = K_u/K_c$ is a measure of closed loop stability robustness, and with K_c given by (5),

$$GM = \frac{\pi}{2}(1+\tau_c/\theta_m). \tag{8}$$

For a given θ_m, the closed loop time constant τ_c must be sufficiently large to guarantee robustness. $\tau_c = \theta_m$ yields GM = π in (8), which is within range GM = 1.7 - 4 recommended in [5].

4. Estimation of atomic oxygen density from spectroscopic measurements using a Kalman filter

Actinometry offers a non-intrusive method for estimating the atomic oxygen density in oxygen-containing plasmas [3]. The emission intensity of the 777nm and 844nm lines may be expressed in the form

$$I_O \propto k_{ex} n_O + k_{dex} n_{O2}, \tag{9}$$

where k_{ex} and k_{dex} are the direct and dissociative excitation rate constants, respectively. Where the dissociation fraction is small, it is clear from (9) that a significant portion of I_O may be due to dissociative excitation. An analagous situation exists in chlorine plasmas and a possible solution to this problem was proposed in [2], where an extended Kalman filter was used to estimate atomic chlorine density. Using the same approach as [2], a Kalman filter may be designed based on the state space process model

$$\begin{aligned}
\frac{dn_{O2}}{dt} &= k_{O2}F_{O2} - \frac{n_{O2}}{\tau_{res}} + w_{O2} \\
\frac{dn_O}{dt} &= k_O F_{O2} - \frac{n_O}{\tau_{res}} + w_O \\
\frac{dk_{O2}}{dt} &= w_{kO2} \\
\frac{dk_O}{dt} &= w_{kO}, \\
I_{777} &= k_{ex,777} n_O + k_{dex,777} n_{O2} + v_{777} \\
I_{844} &= k_{ex,844} n_O + k_{dex,844} n_{O2} + v_{844},
\end{aligned}$$

where $(n_{O2}\ n_{O2}\ k_{O2}\ k_O)'$, $(w_{O2}\ w_{O2}\ w_{kO2}\ w_{kO})'$ and $(v_{777}\ v_{844})'$ are the state, process noise and measurement noise vectors, respectively. The Kalman gain may be derived from the process model and noise statistics [6]. The process gain estimate may be used to adjust the PID controller gain according to (5), in order to maintain a sufficient gain margin.

5. Estimation and control of fluorine density

The relationship between $F^{\star}_{C4F8}$ and n_F may be approximated by the transfer function

$$G_F(s) = \frac{n_F(s)}{F^{\star}_{C4F8}(s)} = \frac{K_F e^{-s\theta_m}}{(s\tau_m + 1)(s\tau_{res} + 1)}, \tag{10}$$

where K_F is a gain term. The transfer functions (3) and (10) differ only in the process gain. Hence, a PID controller with the time constants given by (6) and a gain term given by

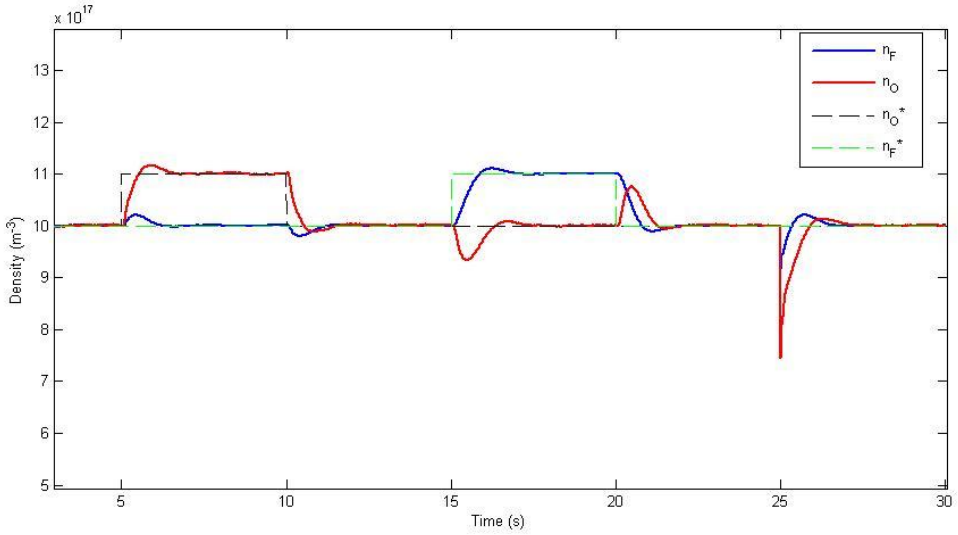
$$K_c = \frac{1}{K_F} \frac{\tau_m + \tau_{res}}{\tau_c + \theta_m}, \tag{11}$$

may be used to control n_F.

6. Results and conclusions

The closed loop responses of atomic oxygen and atomic chlorine to set point changes (shown dashed) and a wall disturbance, represented by a doubling of the atomic oxygen wall recombination coefficient

at 25s, are shown below. The model parameters used were τ_{res} =50ms, τ_m =120ms θ_m = 80ms, $\tau_c = \tau_m$. The closed loop response is seen to be stable with a slight overshoot. In practice, θ_m may be significantly larger than 80ms and systems with large time delays are difficult to control with a PID controller alone. For such systems, an approach such as dead time compensation may be appropriate [5]. In addition, it clear that significant interaction exists between the loops. This interaction may be reduced using decoupling control [5].



Financial support from Science Foundation Ireland via Grant No 07/IN.1/I907 and the contribution of Nina Hanzlikova, who developed the code for the C_4F_8 model, is gratefully acknowledged.

References

[1] J. T. Gudmundsson and E. G Thornsteinsson, Plasma Sources Science and Technology 16, 399-412 (2007)

[2] C. K. Hanish, J. W. Grizzle and F. L. Terry Jr., IEEE Transactions on Semiconductor Manufacturing, 12, 323-331 (1999)

[3] H. M. Katsch, A. Tewes, E. Quandt, A. Goelich, T. Kawetzki and H. F. Doebele, Journal of Applied Physics, 88, 6232-6238 (2000)

[4] G. Kokkoris, A. Goodyear, M. Cooke and E. Gogolides, Journal of Physics D: Applied Physics, 41, 195211 (2008)

[5] D. E. Seborg, T. F. Edgar and D. A. Mellichamp, Process Dynamics and Control, Second Edition, Wiley (2004)

[6] D. Simon, Optimal State Estimation, Wiley (2006)

[7] A. V. Vasenkov, X. Li, G. S. Oehrlein and M. J. Kushner, Journal of Vacuum Science and Technology, A 22, 511 (2004)