Simulation of the Plasma Generated in a Gas Bubble

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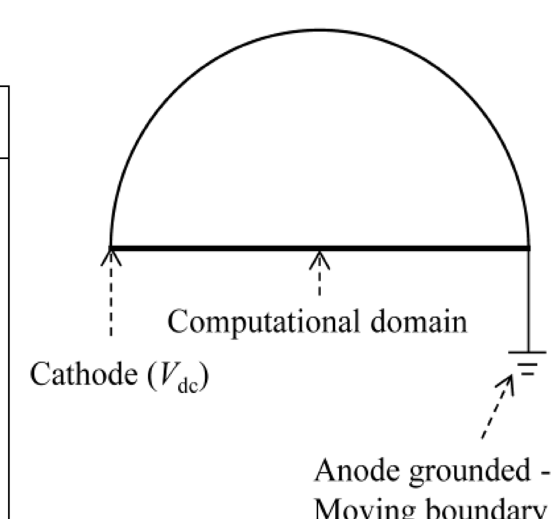
Introduction: The plasmas generated in water involve various physical phenomena such as flows agitated by bubbles, high electric fields for breakdown, discharges in bubbles with the size variation, and so on. In this work, the plasma generated in a gas bubble is studied. The moving mesh technique is coupled for the first time with plasma simulation. The plasma properties during the variation in bubble size are obtained.

Computational Methods: The simulation is performed using 1-D plasma model in a 100%H_2O gas bubble at atmospheric pressure. The bubble radius is varied from 1 to 8.5 mm. The duration for the variation in bubble size is chosen τ = 0.8, 1.6, or 2.4 ms. The plasma species taken in account include the ions: H_2O^+, O_2^+, H_2^+, the neutrals: H_2O, H, OH, H_2, O(^{1}D), O, O_2, O_3, HO_2, H_2O_2, as well as electrons. The chemical reactions in plasmas are listed in Table 1.

Table 1: The chemical reactions in plasmas.

No.	Reactions	σ or k ($m^3 s^{-1}/m^6 s^{-1}$)
1	$e^- + H_2O \rightarrow e^- + H_2O$	σ
2	$e^- + H_2O \rightarrow e^- + H + OH$	σ
3	$e^- + H_2O \rightarrow e^- + H_2 + O(^1D)$	σ
4	$e^- + H_2O \rightarrow 2e^- + H_2O^+$	σ
5	$e^- + H_2 \rightarrow e^- + H_2$	σ
6	$e^- + H_2 \rightarrow e^- + H + H$	σ
7	$e^- + H_2 \rightarrow 2e^- + H_2^+$	σ
8	$e^- + O_2 \rightarrow e^- + O_2$	σ
9	$e^- + O_2 \rightarrow e^- + O + O$	σ
10	$e^- + O_2 \rightarrow e^- + O + O(^1D)$	σ
11	$e^- + O_2 \rightarrow 2e^- + O_2^+$	σ
12	$e^- + O \rightarrow e^- + O(^1D)$	σ
13	$O(^1D) \rightarrow O$	5E-3
14	$2O + O_2 \rightarrow O_3 + O$	3.4E-46*exp(345/T_g)
15	$O + 2O_2 \rightarrow O_3 + O_2$	6E-46*(T_g/300)$^{-2.8}$
16	$H + O + H_2 \rightarrow OH + H_2$	9.19E-45*(T_g/300)$^{-1}$
17	$H + O + H_2O \rightarrow OH + H_2O$	2.76E-44*(T_g/300)$^{-1}$
18	$H + O_2 + H_2 \rightarrow HO_2 + H_2$	5.72E-44*(T_g/300)$^{-0.86}$
19	$H + O_2 + O_2 \rightarrow HO_2 + O_2$	4.86E-44*(T_g/300)$^{-1.24}$
20	$H + O_2 + H_2O \rightarrow HO_2 + H_2O$	4.08E-43*(T_g/300)$^{-0.76}$
21	$H + OH + H_2 \rightarrow H_2O + H_2$	4.92E-43*(T_g/300)$^{-2}$
22	$H + OH + O_2 \rightarrow H_2O + O_2$	6.74E-43*(T_g/300)$^{-2}$
23	$H + O_3 \rightarrow OH + O_2$	2.71E-17*(T_g/300)$^{0.75}$
24	$H + O_3 \rightarrow O + HO_2$	7.51E-19
25	$H + HO_2 \rightarrow H_2O + O$	9.18E-17*exp(-971.9/T_g)
26	$H + HO_2 \rightarrow O_2 + H_2$	1.1E-18*$T_g^{0.56}$*exp(-346/T_g)
27	$H + HO_2 \rightarrow 2OH$	2.35E-16*exp(-373.7/T_g)
28	$O + O(^1D) \rightarrow 2O$	8E-18
29	$O(^1D) + H_2 \rightarrow OH + H$	1.1E-16
30	$O(^1D) + O_2 \rightarrow O + O_2$	4.8E-18*exp(67/T_g)
31	$O(^1D) + O_3 \rightarrow 2O_2$	1.2E-16
32	$O(^1D) + O_3 \rightarrow 2O + O_2$	1.2E-16
33	$O(^1D) + OH \rightarrow H + O_2$	6E-17*$T_g^{-0.186}$*exp(-154/T_g)
34	$O + HO_2 \rightarrow OH + O_2$	2.9E-17*exp(200/T_g)
35	$O(^1D) + HO_2 \rightarrow OH + O_2$	2.9E-17*exp(200/T_g)
36	$O(^1D) + H_2O_2 \rightarrow H_2O + O_2$	5.2E-16
37	$O(^1D) + H_2O \rightarrow O + H_2O$	1.2E-17
38	$O(^1D) + H_2O \rightarrow H_2 + O_2$	2.2E-18
39	$OH + O_3 \rightarrow HO_2 + O_2$	1.69E-18*exp(-941/T_g)
40	$2OH \rightarrow H_2O_2$	1.50E-17*(T_g/300)$^{-0.37}$
41	$OH + HO_2 \rightarrow O_2 + H_2O$	4.38E-17*exp(110.9/T_g)
42	$OH + H_2O_2 \rightarrow H_2O + HO_2$	4.53E-18*exp(-288.9/T_g)
43	$2HO_2 \rightarrow H_2O_2 + O_2$	8.05E-17*(T_g/300)$^{-1}$



1-D bubble plasma model

A dc power supplied voltage V and a ballast resistor R_b are used. V_{dc} is the discharge voltage and j is the the current density. V_{dc} is solved by:

$$V = V_{dc} + jAR_b$$

The moving mesh method, *i.e.*, Arbitrary Langrangian Eulerian (ALE) method, is used to trace the variation in the solved domain.

ALE method comprises of two frames: a reference frame with X coordinate for a 1-D formulation and a spatial frame with x coordinate. The mesh displacement is obtained by solving the following equation

$$\frac{\partial^2}{\partial X^2}\frac{\partial x}{\partial t} = 0$$

Results: The simulation results include the densities of all plasma species, rates for all chemical reactions, electron temperature, electron collision frequency, electric field, and so on.

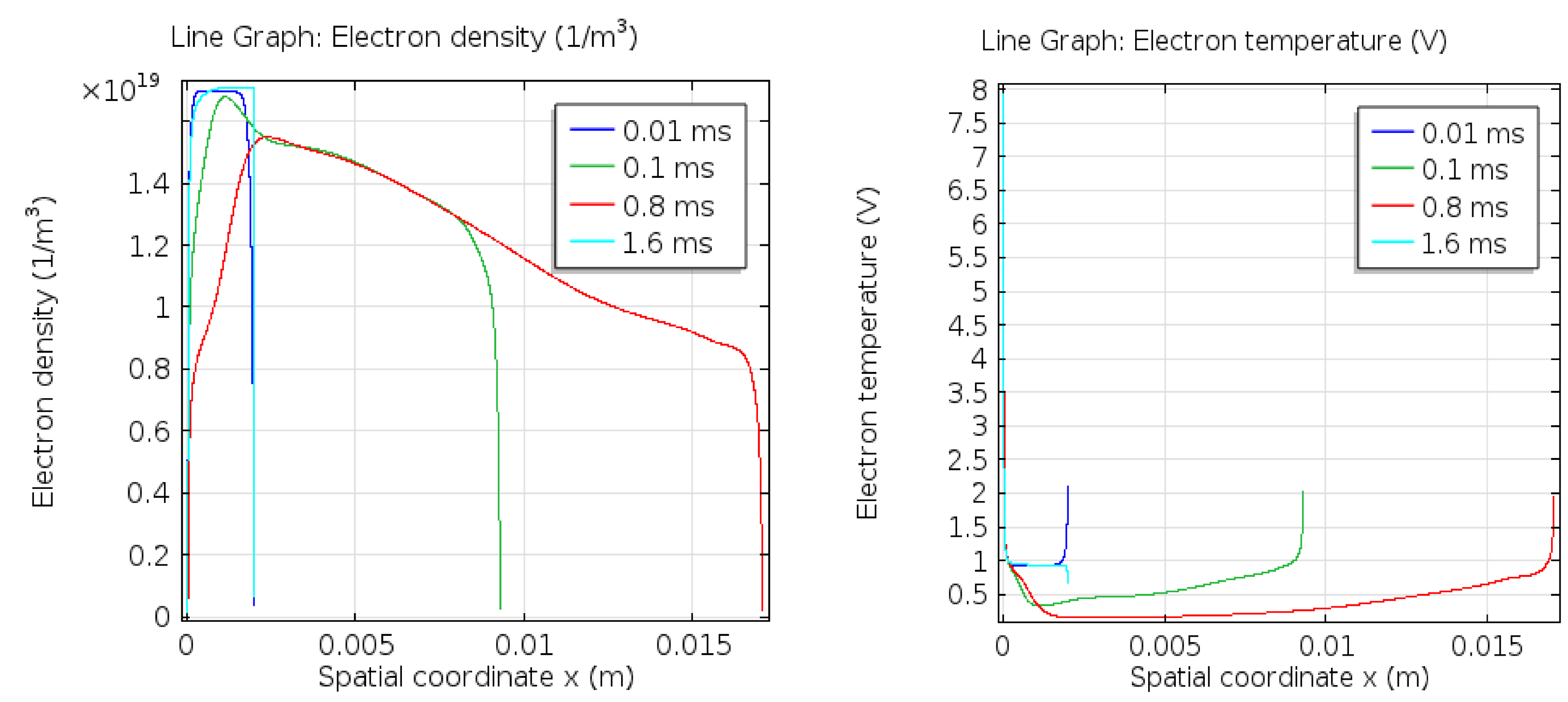


Figure 1. Electron density, electron temperature at the different times for τ = 1.6 ms

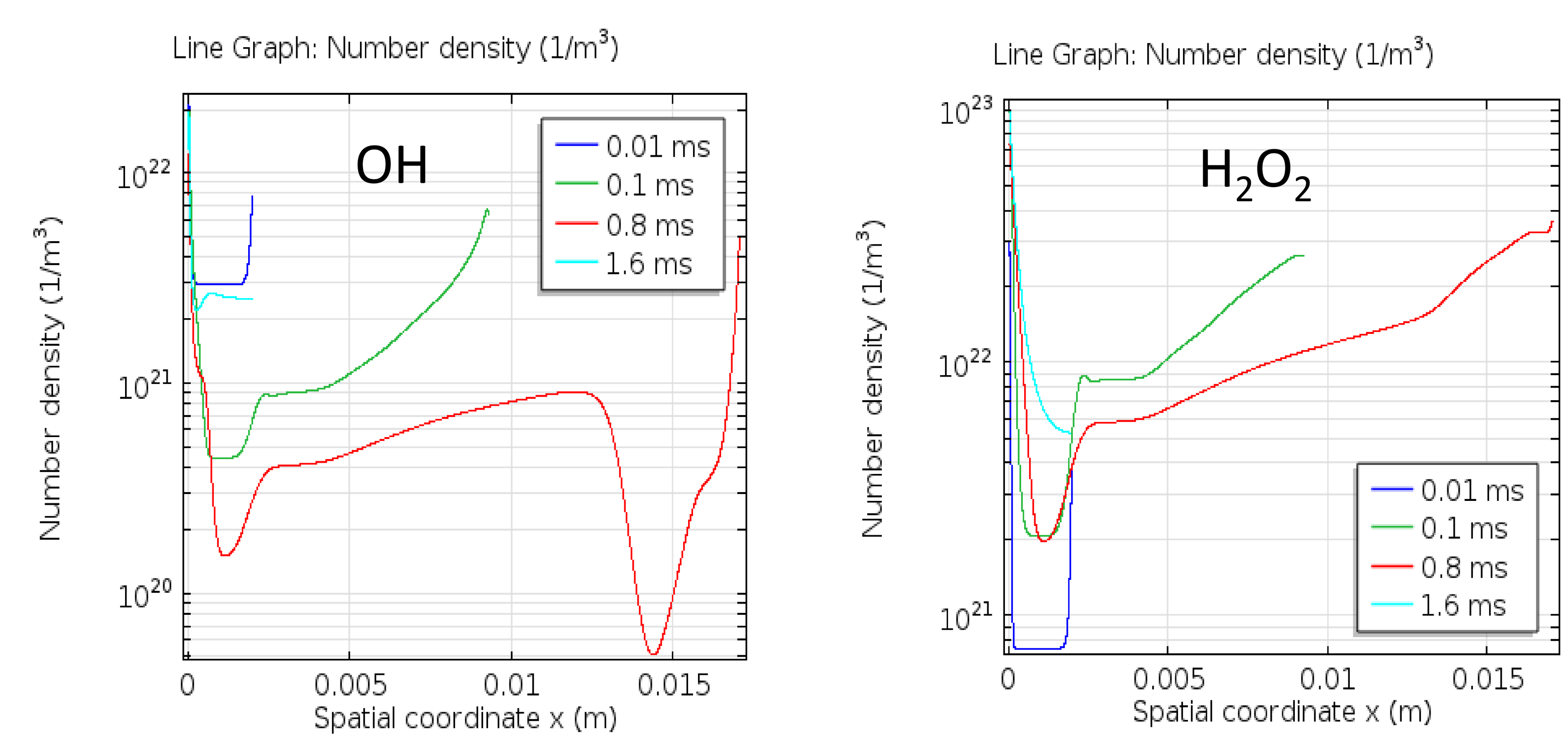


Figure 2. Densities of OH and H_2O_2 species at the different times for τ = 1.6 ms

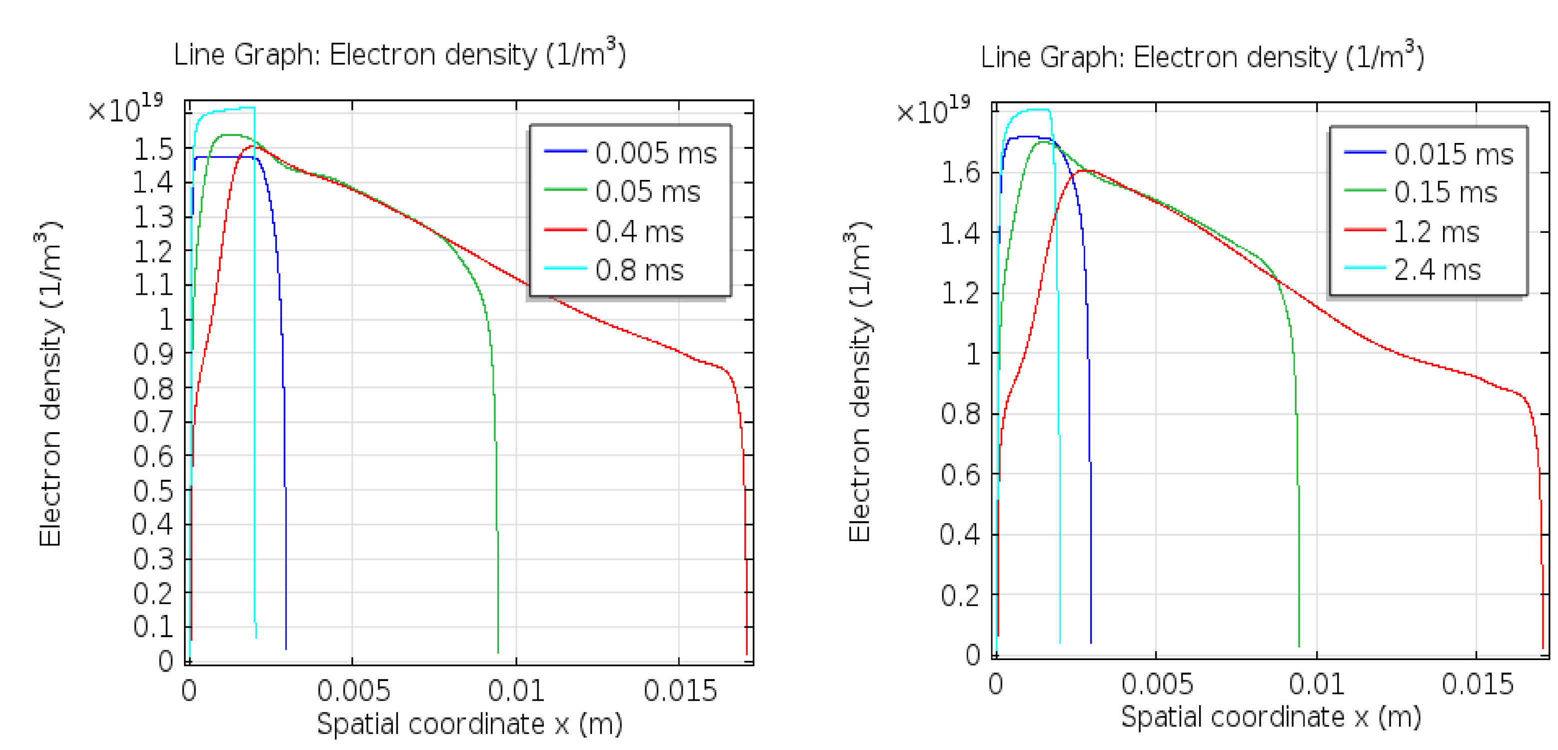


Figure 3. Electron density at the different times for τ = 0.8 and 2.4 ms

Conclusions: This paper presented the study of the plasma generated in a gas bubble. The coupled solution of moving meshing and plasma equations were realized. The obtained distributions of chemical species, such as OH, H_2O_2, and so on, would be beneficial to many further researches on environmental applications. The present research provides an efficient method to study the plasma generated in bubbles, especially in water.

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