The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

Modeling of Nanosecond Pulsed DBD Plasma Actuator for Flow Control

*Jeongheon Chae[1], Sangjun Ahn[2], Hyung-Jin Kim[3] and Kyu Hong Kim[4]

[1), 2), 3), 4)] *Seoul National University, Gwanak-ro 1 Seoul, 151-744, Korea*
[1)] *cjh315@snu.ac.kr*

ABSTRACT

A model of dielectric barrier discharge (DBD) driven by nanosecond pulse was developed for flow control analysis. For analysis of DBD actuator, we solve Gauss's law for electric field, chemical species continuity equation for plasma and Navier-Stokes equation for fluid. Considering all these governing equations makes computational cost enormously expensive due to their time scale difference. By using quasi-1-dimensional self-similar equation of DBD plasma, computational cost can be reduced. The obtained joule heating energy is used to develop a model of dissipating unsteady energy source into fluid by plasma. The developed model reflects change of joule heating energy by the voltage variations during a pulse period. The obtained unsteady energy source term is coupled with Navier-Stokes equation to analyze the flow disturbances made by DBD actuator. The time-varying position of compression wave computed by the developed model was in agreement with previously reported data from experiment. Also, the developed model was able to predict compression wave propagation more accurately compared to a model which used steady energy source term.

1. INTRODUCTION

Nanosecond pulsed DBD plasma actuators has a multi-scale problem. The characteristic time difference between plasma and fluid makes experimental measurement and diagnostics difficult. Thus, numerical study is important and necessary for studying the detailed characteristics of nanosecond pulsed DBD plasma. A lot of research groups put efforts into numerical studies of nanosecond pulsed DBD plasma including plasma-fluid interactions and chemical kinetics. However numerical studies also have difficulties for high computational cost caused by multi-scale problem. To deal with multi-scale problem in computation, a simplified model of nanosecond pulsed DBD plasma was suggested by other researchers [1]. Cheng et al and D.V. Gaitonde et al used semi-empirical method. They used experimental data to make wall

[1), 2), 3)] Ph. D Candidate
[4)] Professor

temperature distribution and joule heating energy distribution. These distributions are used for boundary condition or source term in the computation to analyze the plasma-fluid interaction. Models using semi-empirical method made by experiment data can be used only for limited conditions and do not consider aerodynamic heating and wall temperature changes. K. Takeshima et al [1] and J. G. Zhen used physic-based method, which uses quasi-1-dimension self-similar equations of plasma. They solved Gauss's equation and plasma continuity equations to calculate joule heating energy only at rise time. Since only a part of applied voltage was considered, this model has accuracy problem in various waveforms.

In this study, a model of dielectric barrier discharge (DBD) driven by nanosecond pulse was developed for flow control analysis. The developed model was made by joule heating term calculated from quasi-1-dimensional self-similar equation. The result by the developed model was compared with experimental result for verification.

2. Unsteady Joule Heating Energy Modeling

Quasi-one-dimensional self-similar equation assume steady state plasma after the rise time. However, other parameters as well as electric current are not in steady state. Therefore, DBD plasma model must consider time variation of electric current. In this section, unsteady joule heating energy was modeled based on the solution of quasi-one-dimensional self-similar equation considering unsteady phenomena of plasma.

2.1 Rise Time Period

During rise time, plasma develops as applied voltage increases. Plasma propagates on the dielectric surface with the velocity of V. Thus, electric current also increases by time. Consequently, joule heating energy increases as time goes. It can be said that joule heating energy in this region is depended on the plasma propagation velocity V. The unsteady joule heating model was modeled as follows. Where, Q_{quasi} is joule heating energy obtained from quasi-one-dimensional self-similar equation and ξ_0 is plasma length.

$$Q_{joule}(t,x,y) = Q_{quasi}(\xi_0 - Vt + \xi, y) \quad for \;\; t \le t_{rise} \tag{1}$$

2.2 Plateau Time Period

Even though voltage remains constant during the plateau time, electric current drops rapidly. Therefore, joule heating decreases following normalized time.

$$Q_{joule}(t,x,y) = Q_{joule}(t_{rise},x,y) \cdot f_{plateau}(t_n) \; for \;\; t_{rise} < t \le t_{plateau} \tag{2}$$

2.3 Decay Time Period

In decay time, Joule heating energy increases at the first due to the increases of electric current, but soon it decreases as the applied voltage keeps dropping.

$$Q_{joule}(t,x,y) = Q_{joule}(t_{plateau},x,y) \cdot f_{decay}(t_n) \quad for \;\; t_{plateau} < t \le t_{decay} \qquad (3)$$

2.4 Unsteady Joule Heating Energy Model

Figure 1 shows unsteady joule heating energy model applied on the one of analysis done on this study. For the rise time period, the energy continues to increase. For the plateau time, the energy decreases smoothly. In the decay time region, energy slightly increases at first, but starts to decrease in some time after.

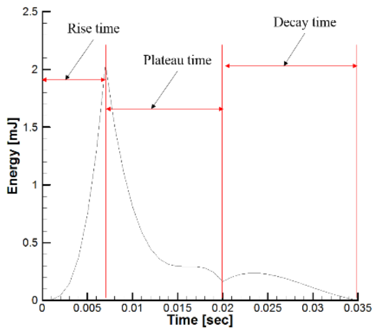

Fig. 1 Example of unsteady joule heating energy source model

3. Numerical Analysis

3.1 Geometry and Grid System

The geometry of DBD actuator in analysis is shown in figure 2. The electrodes are 5 mm in length and their thickness is neglected. Thickness of dielectric barrier is 0.3 mm. Computational domain and mesh system are shown in figure 3.

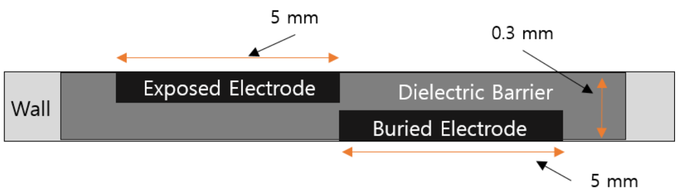

Fig. 2 Geometry of DBD actuator

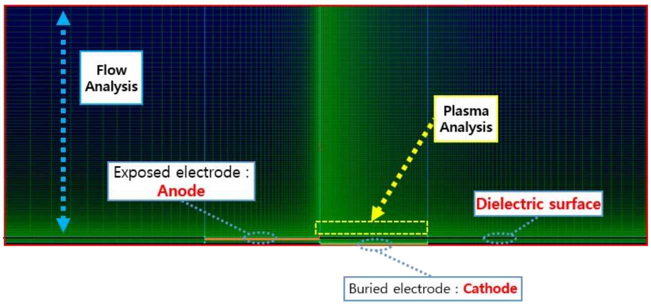

Fig. 3 Computational domain and mesh system

3.2 Boundary and Initial Conditions

Flow analysis conditions are the atmospheric pressure and room temperature. The initial electron number density was set $10^{10}\ m^{-3}$. The initial conditions of flow field are shown in table 1. Detail parameters are shown in table 2.

Table 1 Flow field initial condition

P_∞	$101325\ Pa$
T_∞	$300\ K$
n_{air}	$4.6 \times 10^{26}\ m^{-3}$
n_e	$10^{10}\ m^{-3}$
ϵ_0	$8.85 \times 10^{-12}\ F/m$
ϵ	2.7

Table 2 Applied nanosecond pulse voltage parameters

V_{peak}	τ_{rise}	$\tau_{plateau}$	τ_{decay}	τ_{pulse}
$50\ kV$	$10\ ns$	$26\ ns$	$24\ ns$	$60\ ns$

3.3 Results

Figure 5 shows 2-dimensional joule heating distribution calculated by using quasi-one-dimensional analysis. The joule heating energy distribution is related to the electron number density distribution which is affected by electrode configuration. Peak electron number density and joule heating energy was at the end of exposed electrode.

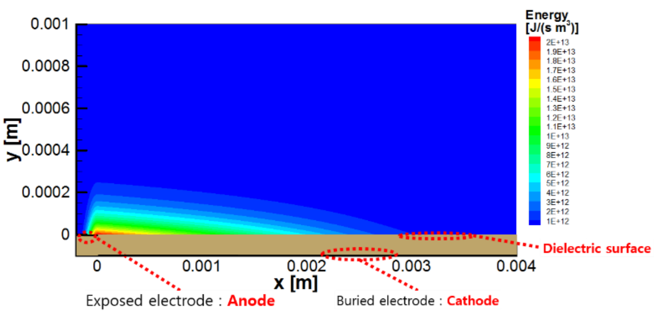

Fig. 5 2-Dimensional joule heating energy distribution

The generated nanosecond pulsed plasma heats flow field rapidly which results in propagating micro shock wave. Figure 6 shows density distribution of flow field at $25\mu s$ and the positions of the shock waves. A cylindrical shock wave was developed at the end of exposed electrode and a planar shock wave was developed over the dielectric surface on buried electrode. Although the plasma responded in nanosecond time scale, the shock wave was developed and observed in microsecond time scale. This results in an asymmetric shock wave in the whole. As those two shock waves continue to propagate, they merge in some time and become a semicircular shock wave. The shock wave become almost symmetric. The developed model shows more accurate result compared to steady-state model for the same energy transfer efficiency, 30%.

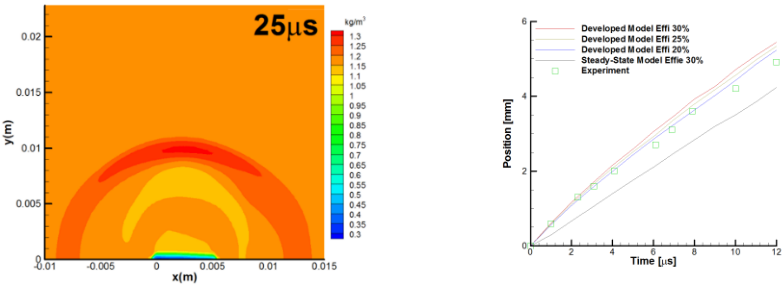

Fig. 6 Density distribution and propagating distance of shock wave

4. CONCLUSTIONS

Modelling of nanosecond pulsed dielectric barrier discharge (DBD) plasma aimed to plasma flow control was done. To reduce computational cost due to characteristic time difference between non-equilibrium plasma and fluid, quasi-one-dimensional governing equation of plasma was used. From calculated plasma parameters, two-dimensional joule heating energy was obtained. The obtained joule heating energy was modeled into unsteady source term of fluid. In the modeling for rise time period, propagating of plasma on the dielectric surface was considered. As plasma propagates with velocity V, increasing joule heating energy was reflected. In the plateau time region, accumulating charged particle was considered, which reduces joule heating energy. In the decay time region, a successive increase and decrease of joule heating energy due to opposite sign current was considered.

Flow analysis was done on room temperature and atmospheric pressure. As a result of applying the unsteady source term obtained by the developed model, propagating micro shock wave was observed. At first, a cylindrical propagating shock wave and a planar shock wave were generated. Later on, they merge together to form a semicircular shock wave. The propagating distances of shock waves are in good agreement with data from literature which are more accurate than steady source model.

ACKNOWLEDGEMENT

This work was conducted at High-Speed Vehicle Research Center of KAIST with the support of Defense Acquisition Program Administration (DAPA) and Agency for Defense Development (ADD).

REFERENCES

K. Takashima, Z. Yin and I. V. Adamovich. (2013), "Measurements and Kinetic Modeling of Energy Coupling in Volume and Surface Nanosecond Pulse Discharges", Plasma Sources Science and Technology, 22.1.

Unfer, T., and J. P. Boeuf. (2009), "Modeling of a Nanosecond Surface Discharge Actuator.", Journal of physics D: applied physics, 42.19.