Numerical Simulations of Linear Single Dielectric Barrier Discharge Plasma Actuators

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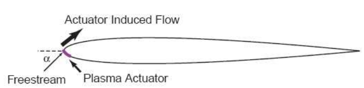
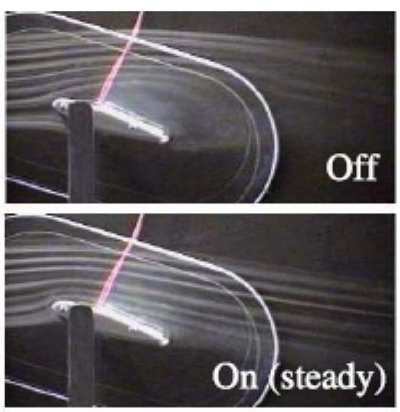
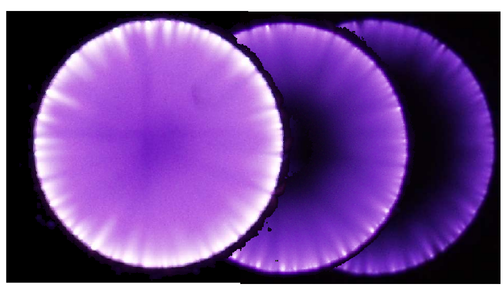
This work is supported by Kentucky NASA EPSCoR through the Kentucky Space Grant Consortium.

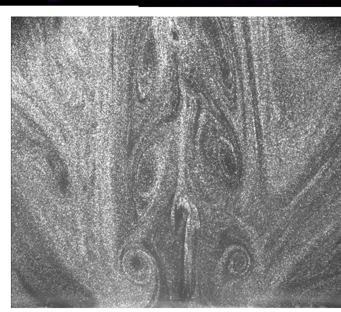
Plasma Actuators





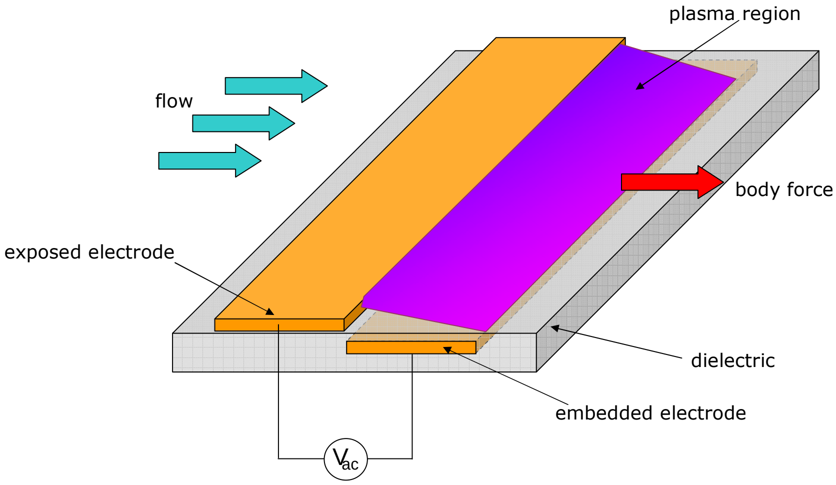
NACA 0015 airfoil at Re=217,000 , $\alpha = 16^o$





M. Post, T. Corke, "Flow Control with Single Dielectric Barrier Plasma Actuators" AIAA Paper 2005-4630, 35th AIAA Fluid Dynamics Conference and Exhibit, 2005.

The Linear DBD Plasma Actuator



3

Model of DBD Plasma Actuator

From Maxwell's Equations: $\nabla \times \vec{E} = \mu_o \frac{\partial \vec{H}}{\partial t}$ Assume: $\frac{\partial \vec{H}}{\partial t} << 1$

$$\Rightarrow \nabla \times \vec{E} \approx 0 \Rightarrow \vec{E} = -\nabla \Phi$$

By superposition: $\Phi = \varphi_1 + \varphi_2$

Gauss's Law states: $\nabla \cdot (\varepsilon \vec{E}) = \rho_c$

$$\Rightarrow \nabla \cdot (\varepsilon \nabla \Phi) = -\rho_c$$

Note that: $\varepsilon = \varepsilon_r \varepsilon_o$, where $\varepsilon_o =$ permittivity of free space

4

Model of DBD Plasma Actuator

Combining yields two equations:

$$\boxed{\nabla\cdot(\varepsilon_r \nabla \varphi_1) = 0} \qquad \boxed{\nabla\cdot(\varepsilon_r \nabla \varphi_2) = -\rho_c / \varepsilon_o}$$

$\dfrac{\rho_c}{\varepsilon_o}$ can be written as: $\dfrac{\rho_c}{\varepsilon_o} = \left(-\dfrac{1}{\lambda_d^2}\right)\varphi_2$ *

Where λ_d is the Debye length (length scale of plasma),

$\varphi_1 = \phi$ is the potential due to the electric field and

$\varphi_2 = \rho_c$ is the net charge density.

$$\boxed{\nabla\cdot(\varepsilon_r \nabla \phi) = 0} \qquad \boxed{\nabla\cdot(\varepsilon_r \nabla \rho_c) = \rho_c / \lambda_d^2}$$

* Enloe, McLaughlin, et al. "Mechanisms and Responses of a Single Dielectric Barrier Plasma Actuator: Geometric Effects", AIAA Journal, Vol. 42, No. 3, 2004.

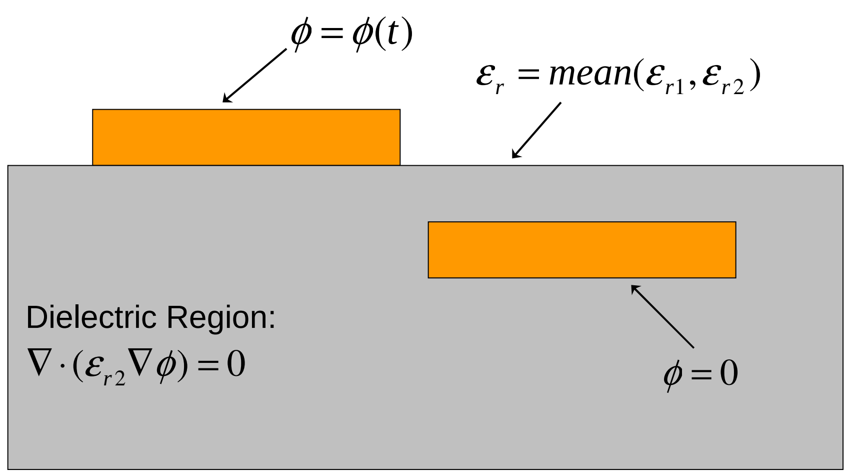
5

Potential Due to Electric Field BC's

Fluid Region:

$$\nabla\cdot(\varepsilon_{r1}\nabla\phi) = 0$$

Outer Boundaries: $\dfrac{\partial\phi}{\partial\vec{n}} = 0$



6

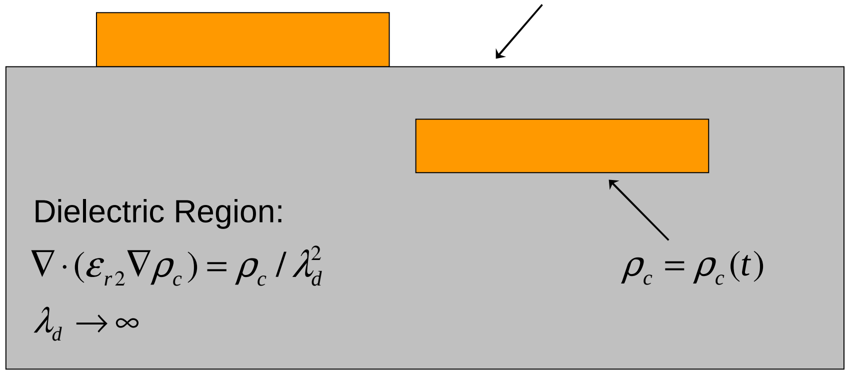
Charge Density BC's

Fluid Region:

$$\nabla \cdot (\varepsilon_{r1} \nabla \rho_c) = \rho_c / \lambda_d^2$$

Outer Boundaries: $\rho_c = 0$

$$\varepsilon_r = mean(\varepsilon_{r1}, \varepsilon_{r2})$$



Dielectric Region:

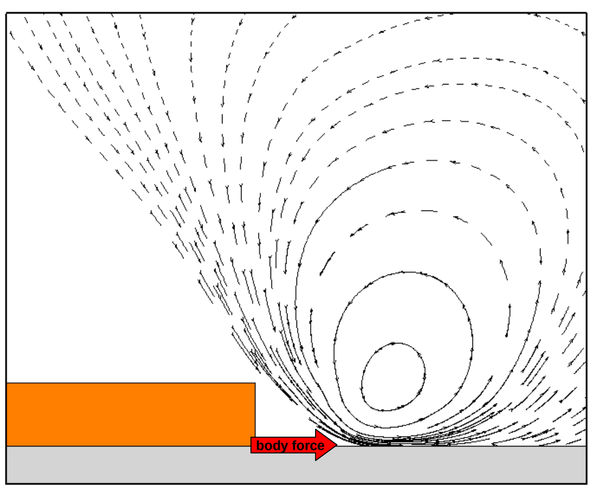
$$\nabla \cdot (\varepsilon_{r2} \nabla \rho_c) = \rho_c / \lambda_d^2$$

$$\lambda_d \to \infty$$

$$\rho_c = \rho_c(t)$$

Effects of the Plasma Actuator

Body Force Vector: $\vec{f}_b = \rho_c \vec{E} = \rho_c (-\nabla \phi)$



Model Parameters

$$\varepsilon = \varepsilon_r \varepsilon_o, \text{ where } \varepsilon_o = 8.8542 \times 10^{-12}\,\mathrm{C^2 N^{-1} m^{-2}}$$

Air $\varepsilon_{r1} = 1.0$

Kapton $\varepsilon_{r2} = 2.3$

← Material Properties

$$\lambda_d = 0.00017\,\mathrm{m}$$ ← Empirical Value

$$\phi^{max} = 5\,\mathrm{kV}$$ ← Experimental Input

$$\rho_c^{max} = 0.00750\,\mathrm{Cm^{-3}}$$ ← **Arbitrary Parameter**

9

Kentucky Fluid Clusters

KFC6A – 23 AMD Athlon 64x2 4600+

KFC6I – 24 Intel Core 2 Duo e6400

KFC5 – 47 AMD Athlon 64 3200+

KFC4 – 48 AMD XP 2500+

KFC3 – 32 Intel Pentium 4 2.8GHz

10

UNCLE

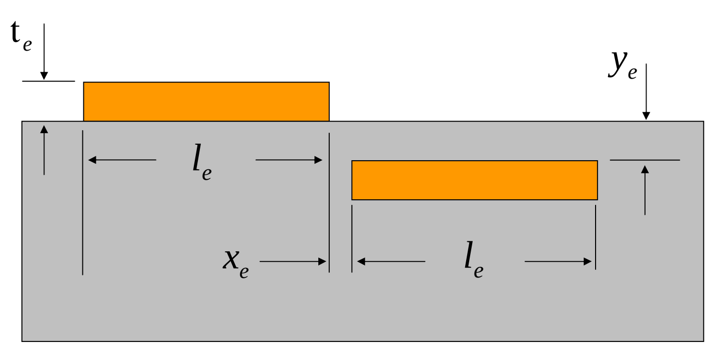
- Originally written by Dr. George P. Huang while at UK
- 2D/3D unstructured, finite volume based, incompressible Navier-Stokes solver
- 2^{nd} order upwind scheme for advection terms
- 2^{nd} order centered difference for diffusion terms
- 2^{nd} order fully implicit time discretization
- Momentum - collocated grid with Rhie and Chow interpolation method
- Pressure - cell-centered-based method similar to SIMPLE
- Turbulence - one-equation Spalart-Allmaras and two-equation Menter SST
- 2^{nd} order centered difference for additional potential equations

UK

11

Dimensions of Actuator

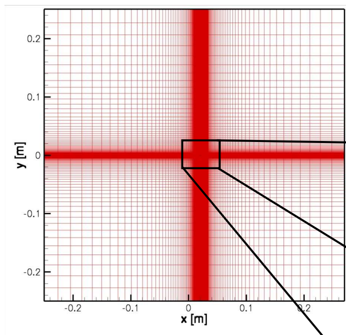
$$l_e = 10\text{mm} \qquad \mathrm{t}_e = 0.102\text{mm}$$
$$x_e = 0.5\text{mm} \qquad y_e = 0.127\text{mm}$$



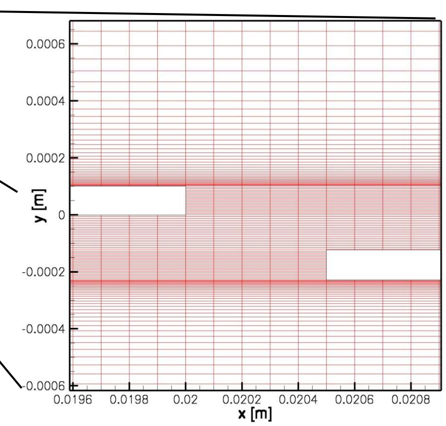
UK

12

Grid Generation



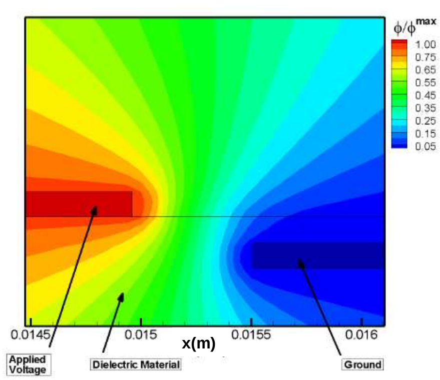
Grid Generation using Gambit
80,000 grid points



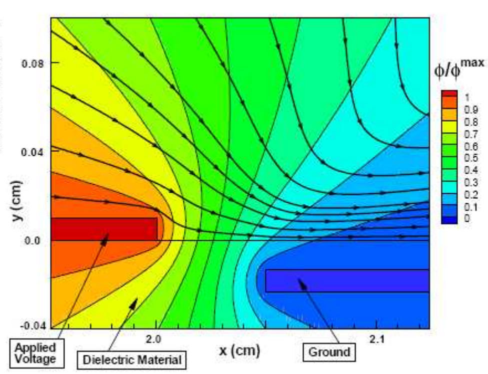
$$\min(\Delta y) \approx 2.0\times10^{-6}\,\mathrm{m}$$
$$\min(\Delta x) \approx 1.0\times10^{-4}\,\mathrm{m}$$
$$\min(Area) \approx 2.0\times10^{-10}\,\mathrm{m}^2$$

Potential Due to Electric Field

UNCLE Results



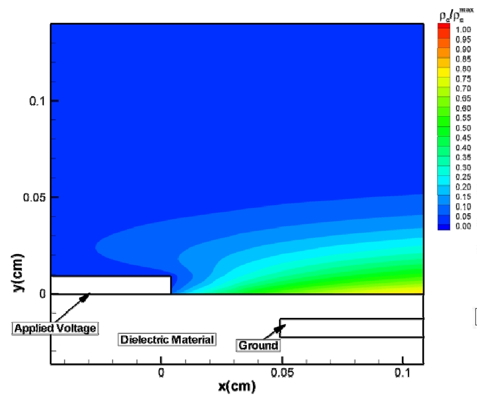
GHOST Results



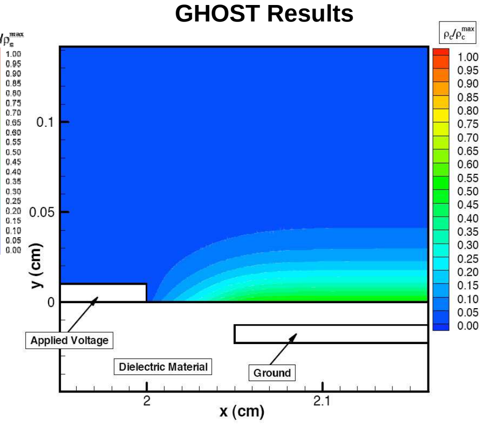
Y.B. Suzen, P.G. Huang, J.D. Jacob, D.E. Ashpis "Numerical Simulations of Flow Separation Control in Low-Pressure Turbines using Plasma Actuators." 45th AIAA Aerospace Sciences Meeting and Exhibit, Reno NV, 2007.

Normalized Net Charge Density

UNCLE Results



GHOST Results



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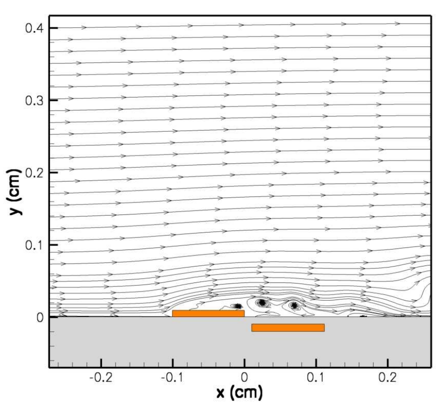
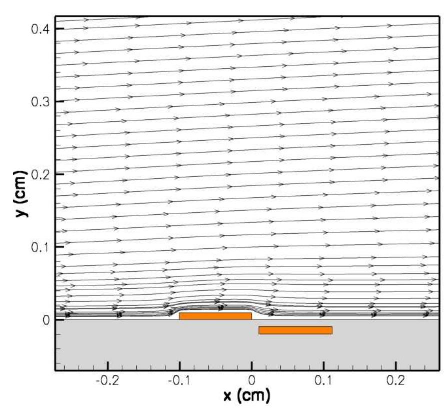
15

Preliminary Cross Flow Results



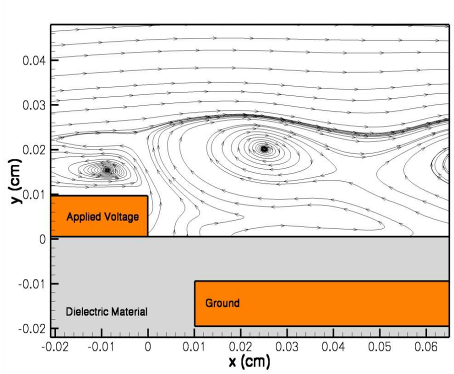
Crossflow results **without** Plasma Actuator



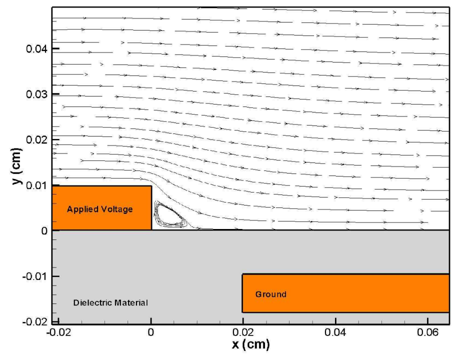
Crossflow results **with** Plasma Actuator

16

Preliminary Crossflow Results



Crossflow results without Plasma Actuator



Crossflow results with Plasma Actuator

17

Future & Ongoing Work

- Verify results through comparisons with experimental and numerical data
  - quantitative comparisons with experiments in quiescent flow
- Simulate separation control on airfoils/turbine blades
- Expand to three dimensions
  - Implement and compare with experimental data from the annular plasma actuator synthetic jet (PASJ) by Jacob, Santhanakrishnan.

18

Questions?