University of Tennessee

Plasma Sciences Laboratory

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THE PHYSICS AND PHENOMENOLOGY OF PARAELECTRIC ONE ATMOSPHERE UNIFORM GLOW DISCHARGE PLASMA (OAUGDPä) ACTUATORS FOR AERODYNAMIC FLOW CONTROL*

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ABSTRACT

In this paper, we present data on the physics and phenomenology of plasma actuators based on the One Atmosphere Uniform Glow Discharge Plasma (OAUGDP™) that may be useful in optimizing the paraelectrically induced flow velocity. It is shown that the real (as opposed to reactive) power delivered to an actuator is divided between dielectric heating of the insulating panel, and power delivered to the plasma that is available for flow acceleration. The correspondence between the power input to the plasma and the flow velocity is presented, along with a discussion of selecting the RF voltage, frequency, electrode gap distance, and dielectric material that optimizes the induced flow velocity of a single actuator for a given power input to the plasma. Induced flow velocities in air of 5+ m/sec from a single Teflon dielectric plasma actuator, and 10+ m/sec from a series array of 8 such electrodes will be reported.

PLASMA ACTUATORS

- *Plasma actuators* use Electrohydrodynamic (EHD) or Magnetohydrodynamic (MHD) forces to accelerate boundary layer flows by adding momentum but not mass.
- *Paraelectric* plasma actuators use the paraelectric EHD body force that acts on the net charge density of a plasma*.
- Such paraelectric plasma acceleration is the electrostatic analog of paramagnetism, because plasma is accelerated by an electric field gradient.
- The plasma is coupled to the neutral gas flow by Lorentzian collisions between the plasma ions and the neutral gas.
- Research effort on plasma actuators is increasing at a rapid rate. A Google search on “plasma actuator” produced the following numbers of hits:

August, 2003	19 hits
January 2005:	137 hits

*See J. R. Roth, Industrial Plasma Engineering, Vol 2, Section 18.6

NORMAL GLOW STRUCTURES IN THE CO-PLANAR ONE ATMOSPHERE UNIFORM GLOW DISCHARGE PLASMA (OAUGDPÔ) ACTUATOR

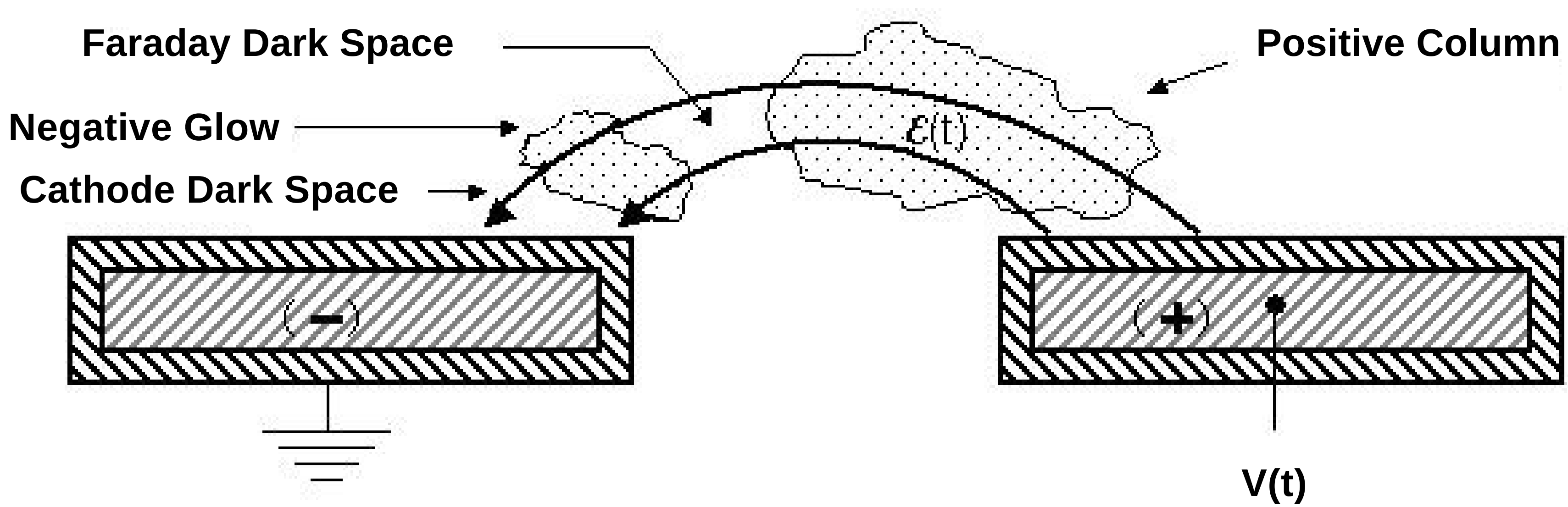


Figure 1: Features of the co-planar plasma actuator during half an RF cycle of the One Atmosphere Uniform Glow Discharge Plasma (OAUGDPÒ).

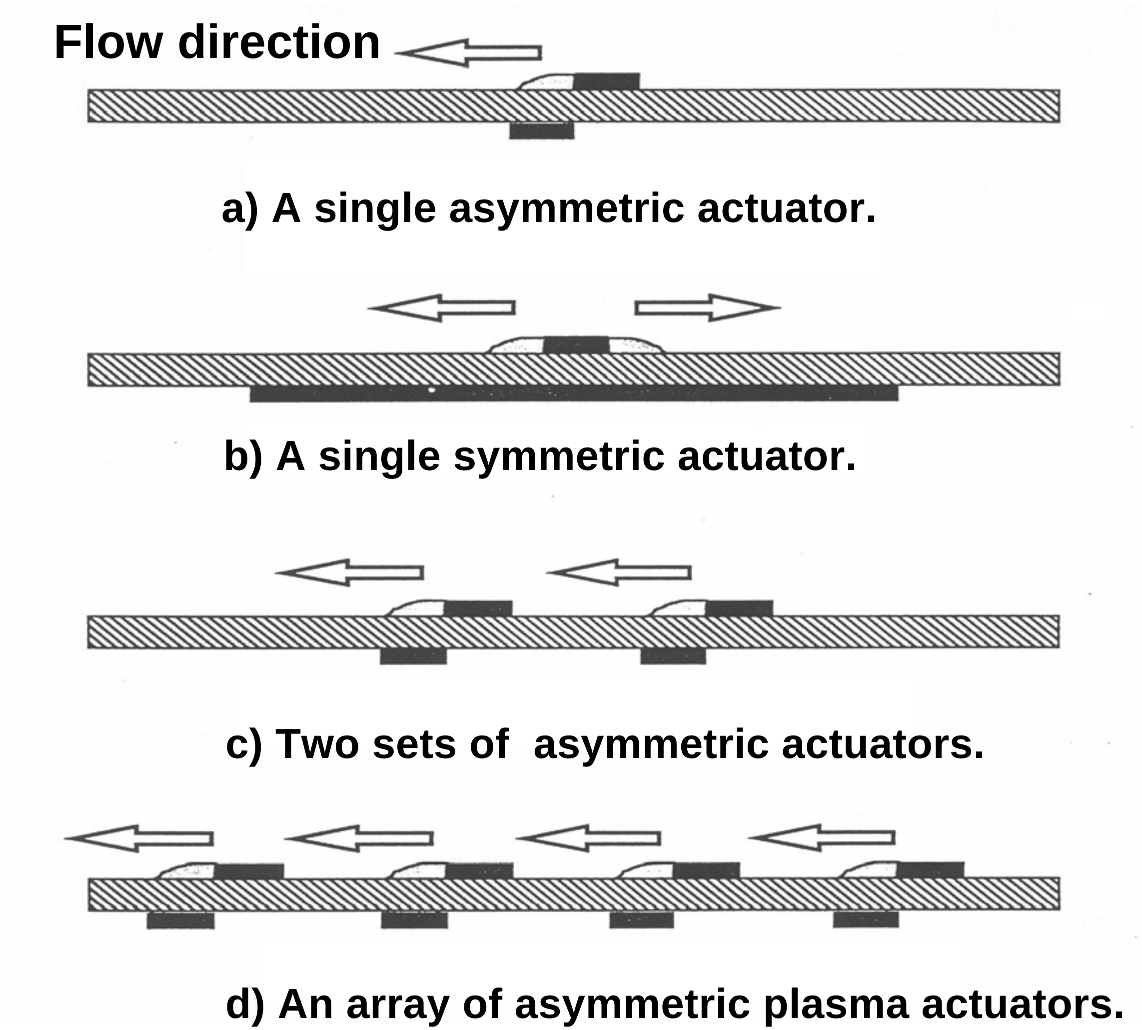
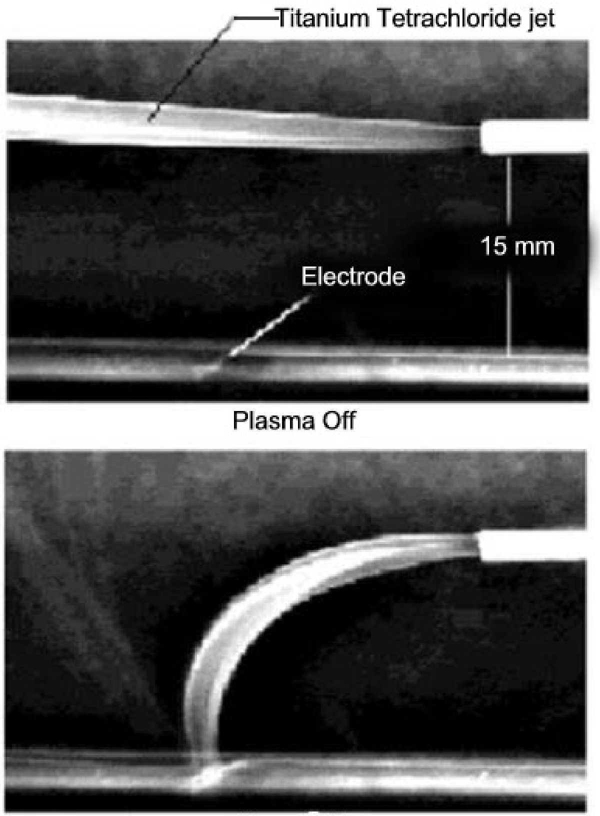


Figure 2. Plasma actuator geometries for paraelectric flow.

PARAELECTRIC FLOW ACCELERATION DISCLOSED BY A SMOKE JET



Plasma On
E=4.5 kV rms, f=3 kHz

Figure 3

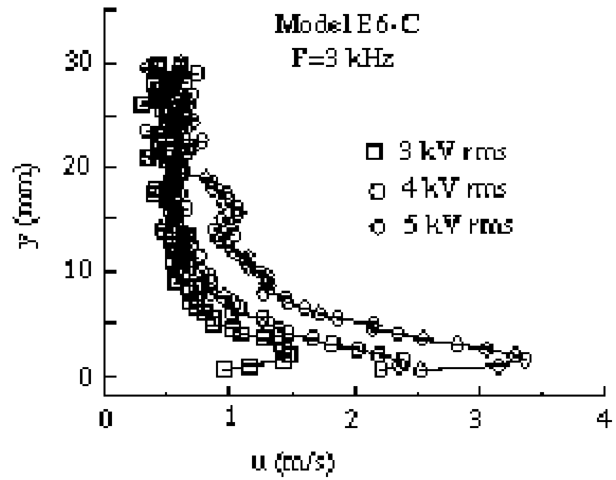


Figure 4

You can download a film clip of Fig.3 from http://plasma.ee.utk. edu/~plasma/video/plasma1. mov

CHARACTERISTIC PLASMA ACTUATOR PANELS

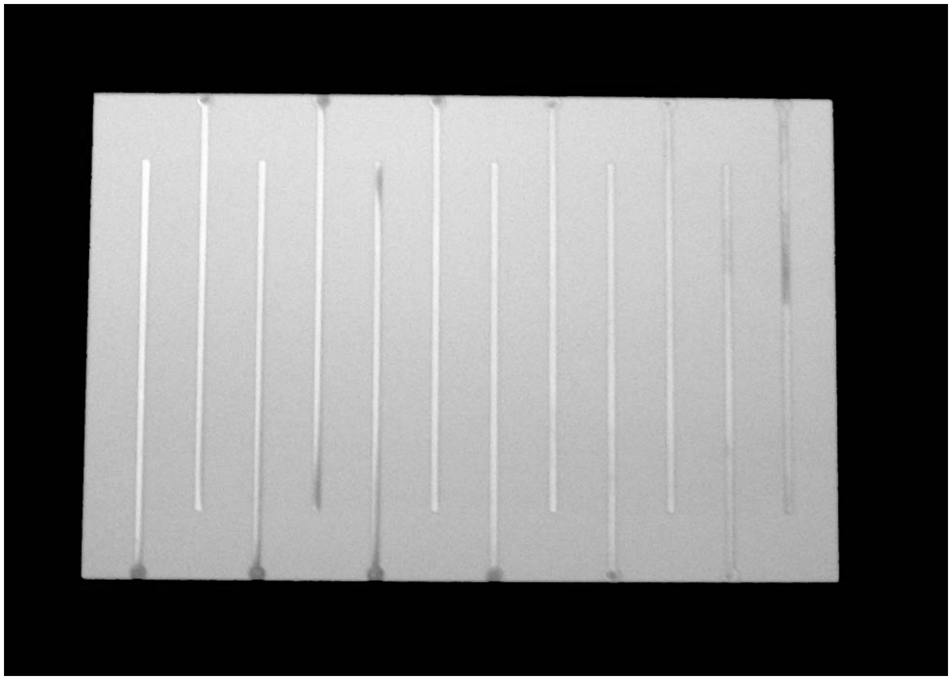
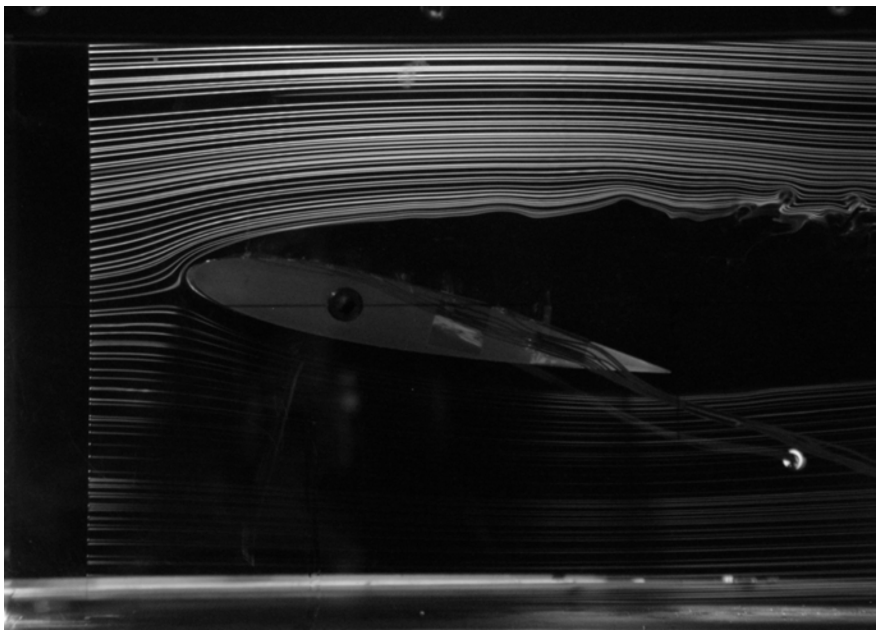


Figure 5: Flat ceramic (Al_2O_3) panel

Figure 6: Flexible KaptonÒ Panel

FLOW ATTACHMENT USING 8 PLASMA ACTUATORS ON A FLEXIBLE KAPTON PANEL

Plasma Off



Plasma On

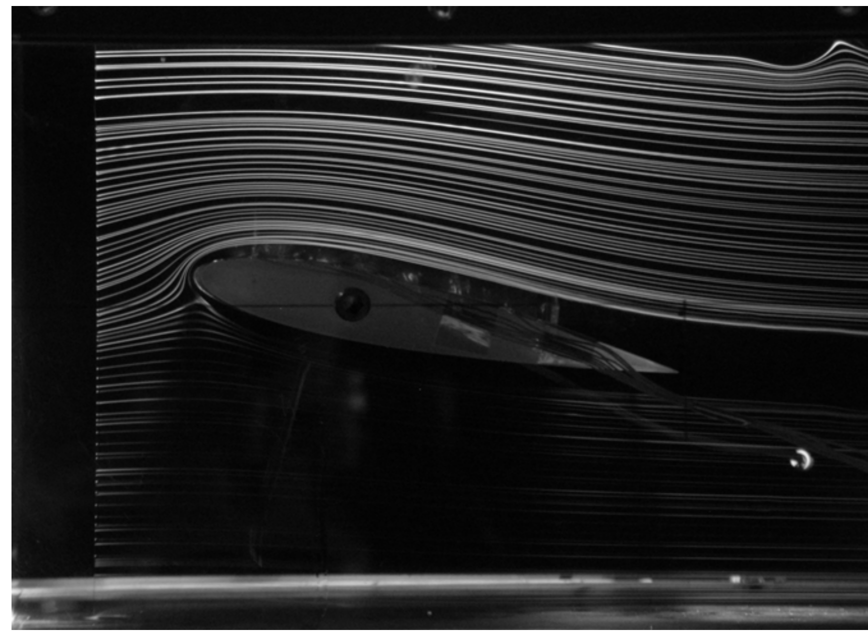


Figure 7: NACA 0015 airfoil in wind tunnel with velocity 2.85 m/sec, 12 degree angle of attack, actuator voltage 3.6 kV, actuator frequency = 4.2 kHz

Figure 7a Smoke trails with wind tunnel velocity of 1.6 meters/sec and paraelectric plasma actuators not energized. There is a small degree of boundary layer growth from a flow-tripping disturbance near the leading edge of the panel.

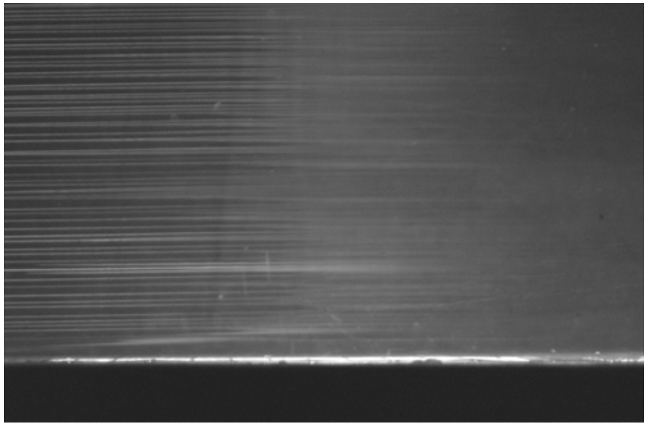
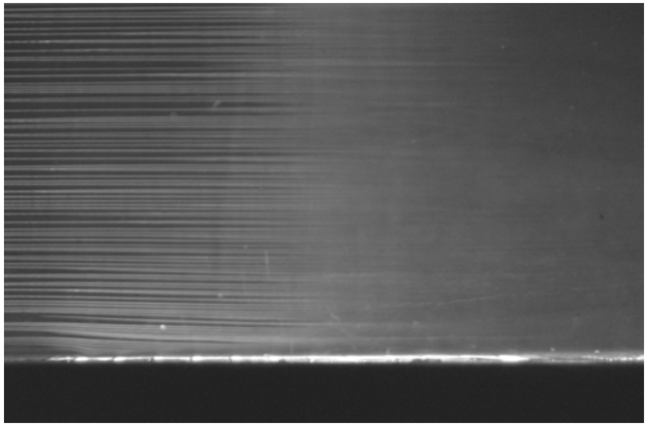


Figure 7b Smoke trails with wind tunnel velocity of 1.6 meters/sec and paraelectric plasma actuators energized.



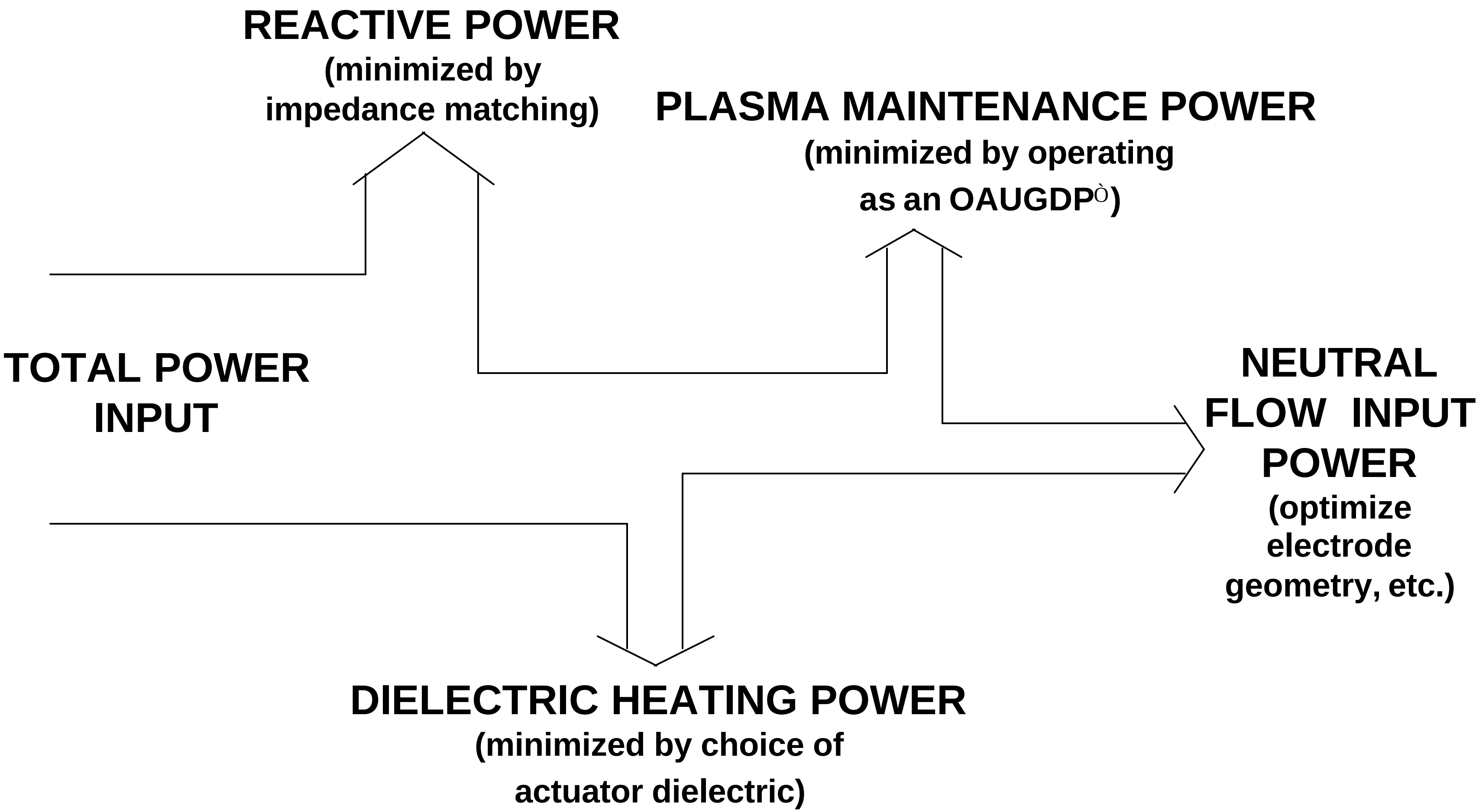


Figure 8. Schematic illustration of the power flow to a plasma actuator.

DESIGN ISSUES FOR PLASMA ACTUATORS

1.) Plasma versus dielectric heating power input.

2.) Minimizing dielectric heating input power.

3.) Choice of dielectric material for plasma actuators.

4.) Optimum actuator geometry for flow acceleration.

5.) Maximizing paraelectrically induced flow velocity.

DIELECTRIC HEATING OF DIELECTRIC MATERIALS

$$P = U^{2}_{max} \frac{2pfA}{d} e_{r} e_{o} \tan d \qquad (1)$$

$$P = KU^{2}f \qquad (2)$$

Where

A	**=**	**electrode area, square meters.**
d	**=**	**electrode thickness, meters.**
f	**=**	**frequency of applied voltage, Hertz**
K	**=**	**dielectric heating constant, Watts/kilovolt2-Hertz.**
P	**=**	**dielectric power loss, Watts.**
tan *d*	**=**	**loss tangent of dielectric**
***U*rms, *U*max**	**=**	**rms and maximum voltage across dielectric respectively, Volts**
e* o, *e r	**=**	**free space and relative permittivity respectively, Farad/meter.**
?	**=**	**mass density of dielectric material, kg/m^3**

One can determine the constant K in Eq. 2 by running the actuator(s) below the plasma initiation voltage and measuring the input power.

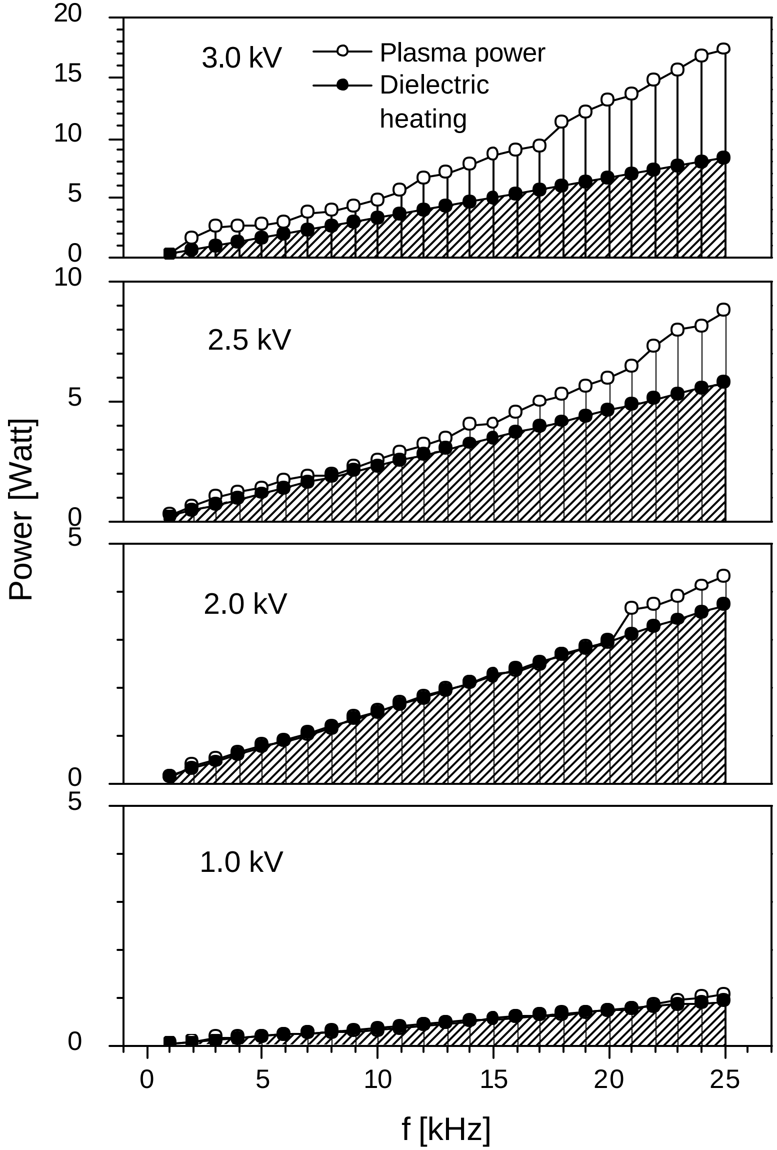


Figure 9. Single ceramic (Al_2O_3) actuator power dissipation as a function of voltage and frequency.

o - Total plasma power.

• - Dielectric heating calculated from Eq. (2) for K=0.04 $W.kHz^{-1}\ kV^{-2}$.

Un-hatched area below open data points is the net plasma power.

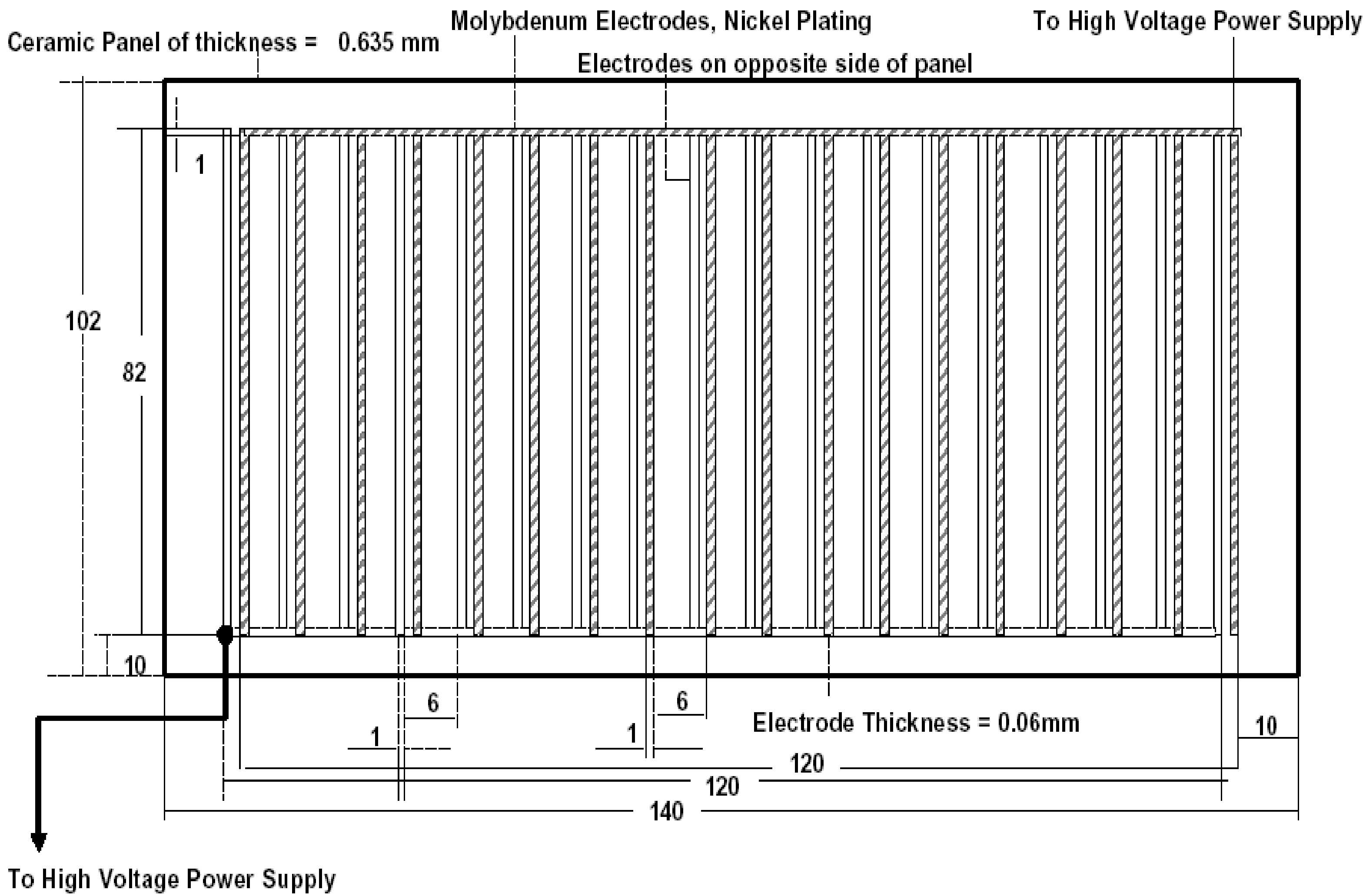


Figure 10 Details of ceramic (Al_2O_3) panel with 18 actuators.

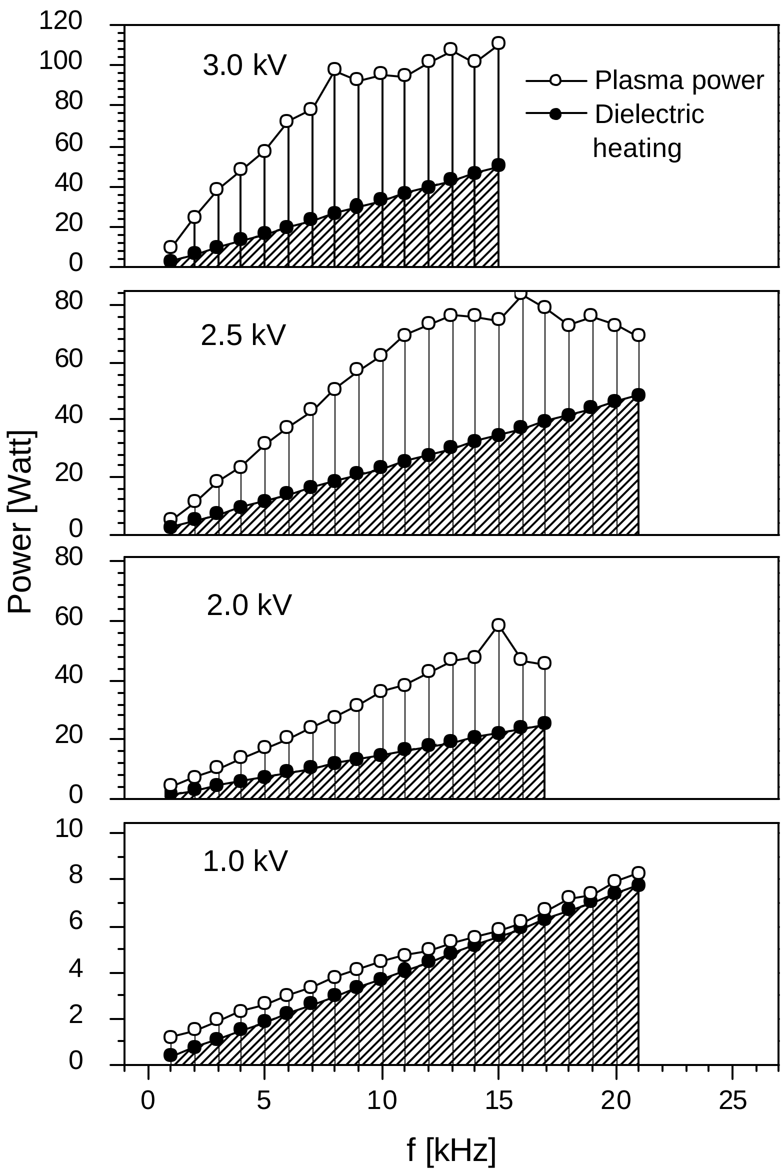


Figure 11. Eighteen actuator ceramic (Al_2O_3) panel power dissipation as a function of RF voltage and frequency.

o - Total plasma power.

• - Dielectric heating calculated from Eq. (2) for K=0.37 W.kHz^{-1} kV^{-2}.

Unhatched area below open data points is the net plasma power.

RESOLUTION OF POWER INPUT TO PLASMA

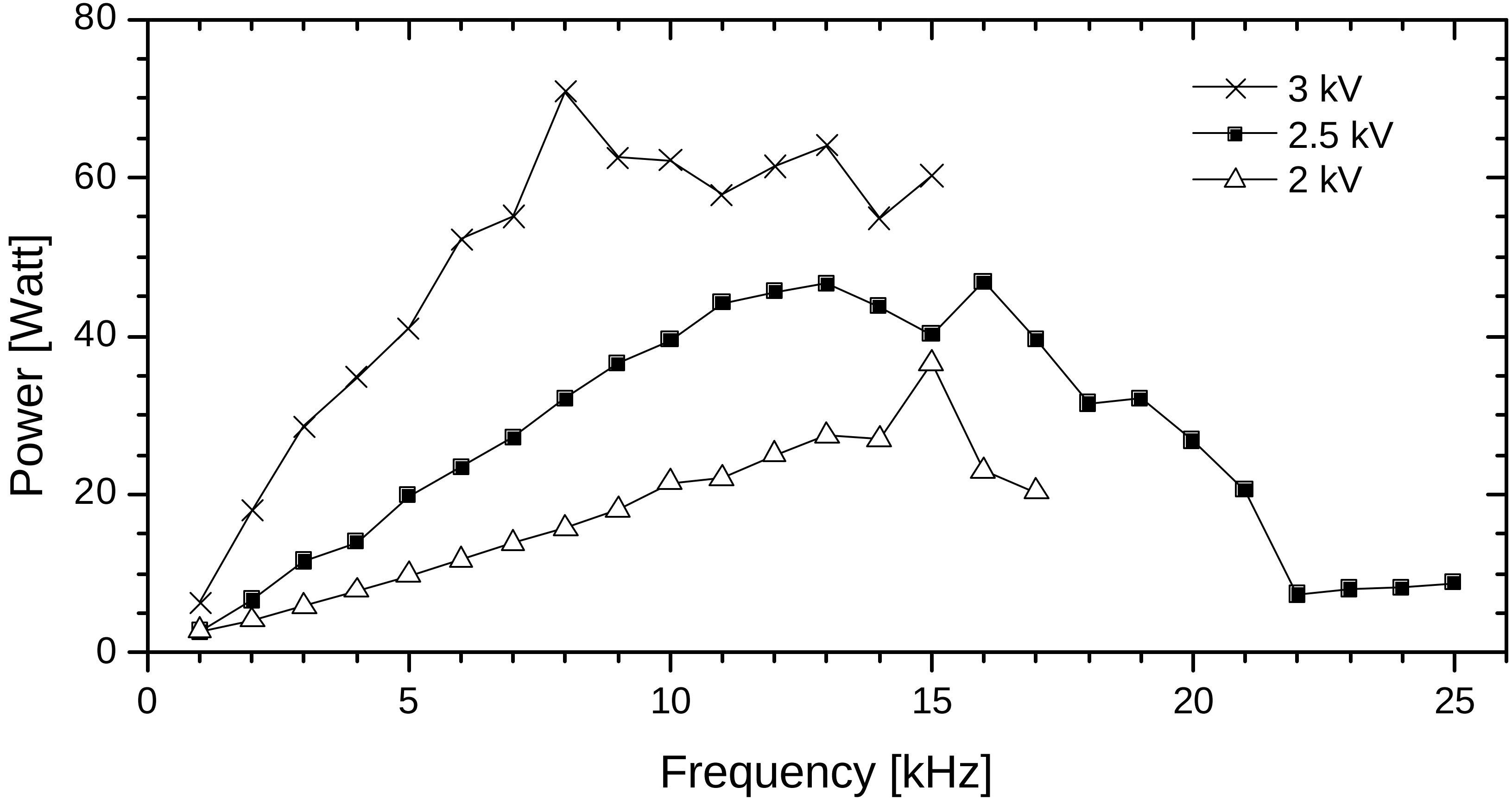


Figure 12. Net power input to the plasma for an 18-actuator panel, the difference of the total power and dielectric heating of Figure 11.

TABLE 1. CHARACTERISTICS OF CANDIDATE DIELECTRIC MATERIALS

Material	Mass density ρ (kg/m^3)	Dielectric constant (ε_r) (room temperature)	Dielectric Strength (*E*) (room temperature)	Dielectric loss $\tan\delta$ (1MHz)	Loss Factor $\varepsilon_r \times \tan\delta$	Overall Rank Index‡	Reference
Air	1.3	1	3kV/mm				
Quartz	2200	5	25kV/mm	0.00001	0.00005	3	CEVP Ltd.
Kapton™	1420	3.5	154kV/mm	0.009 (100kHz)	0.0315	4	DuPont
Lexan™	1190	2.9 (1MHz)	16kV/mm	0.0085	0.02465	4.67	GE Plastics
Teflon™	2160	2.1	11.2kV/mm	0.0001	0.00021	5.33	DuPont
Bakelite	1420	5~22	24kV/mm	0.02	0.1~0.44	5.33	McMaster
Mica	2800	4~9	25kV/mm	0.0013	0.0052~0.0117	5.33	MatWeb
PC Board	1690	5	16.8kV/mm	0.005	0.025	5.67	Corning
Pyrex® glass	2530	4.1 (1MHz)	15kV/mm	0.005	0.0205	6.67	DuPont
Aluminum Oxide	3700	9.4 (1MHz)	15kV/mm	0.0004	0.00376	7	MatWeb
Glass	2600	3.8	10kV/mm	0.004	0.0152	7.67	KYOCERA

‡Overall Rank Index is the average of rank in Dielectric strength, loss factor, and mass density.)

DIELECTRIC CONSTANT OF CANDIDATE PLASMA ACTUATOR MATERIALS

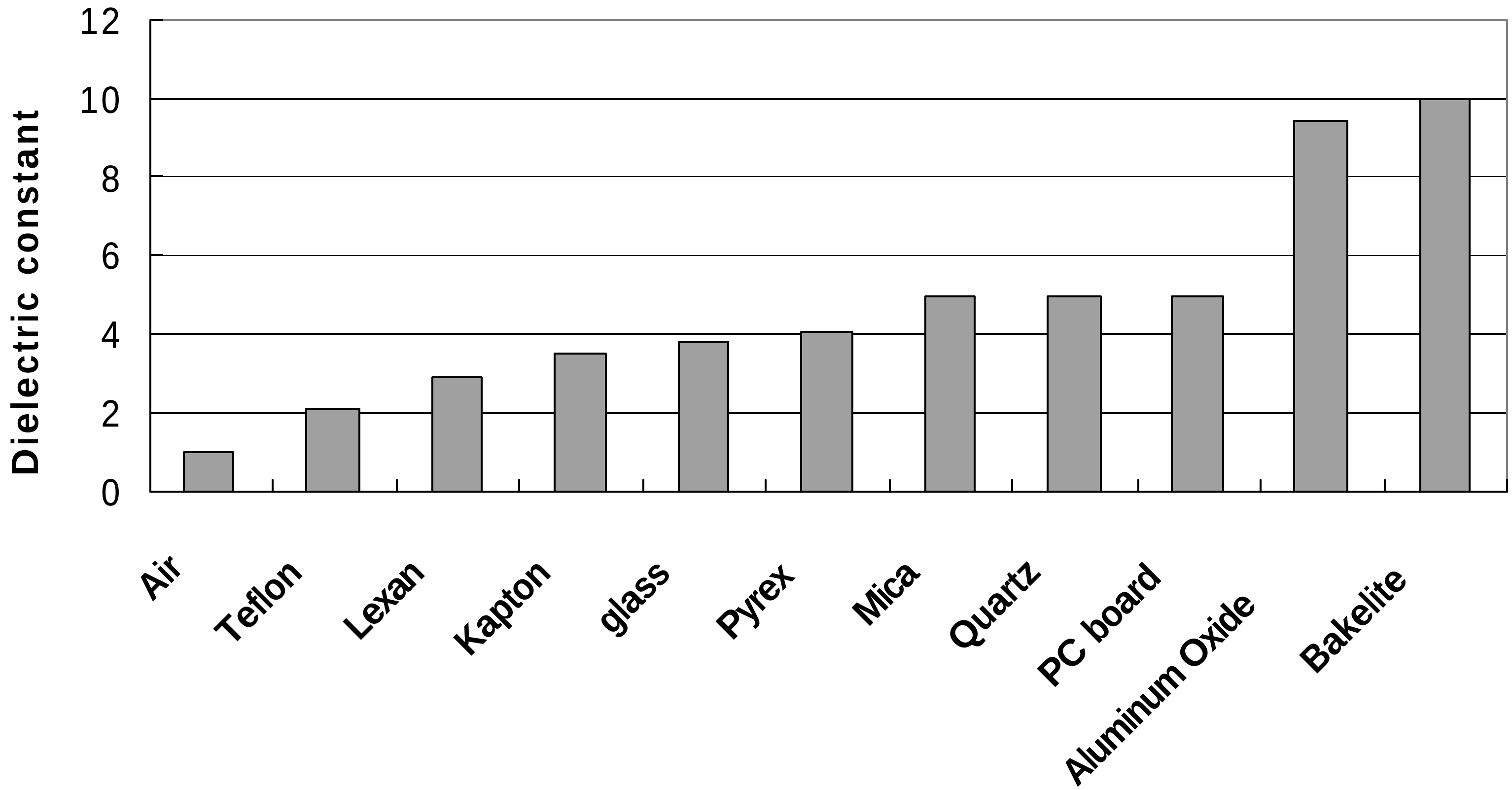


Figure 13 Dielectric constant of candidate actuator dielectrics

DIELECTRIC STRENGTH OF CANDIDATE PLASMA ACTUATOR MATERIALS

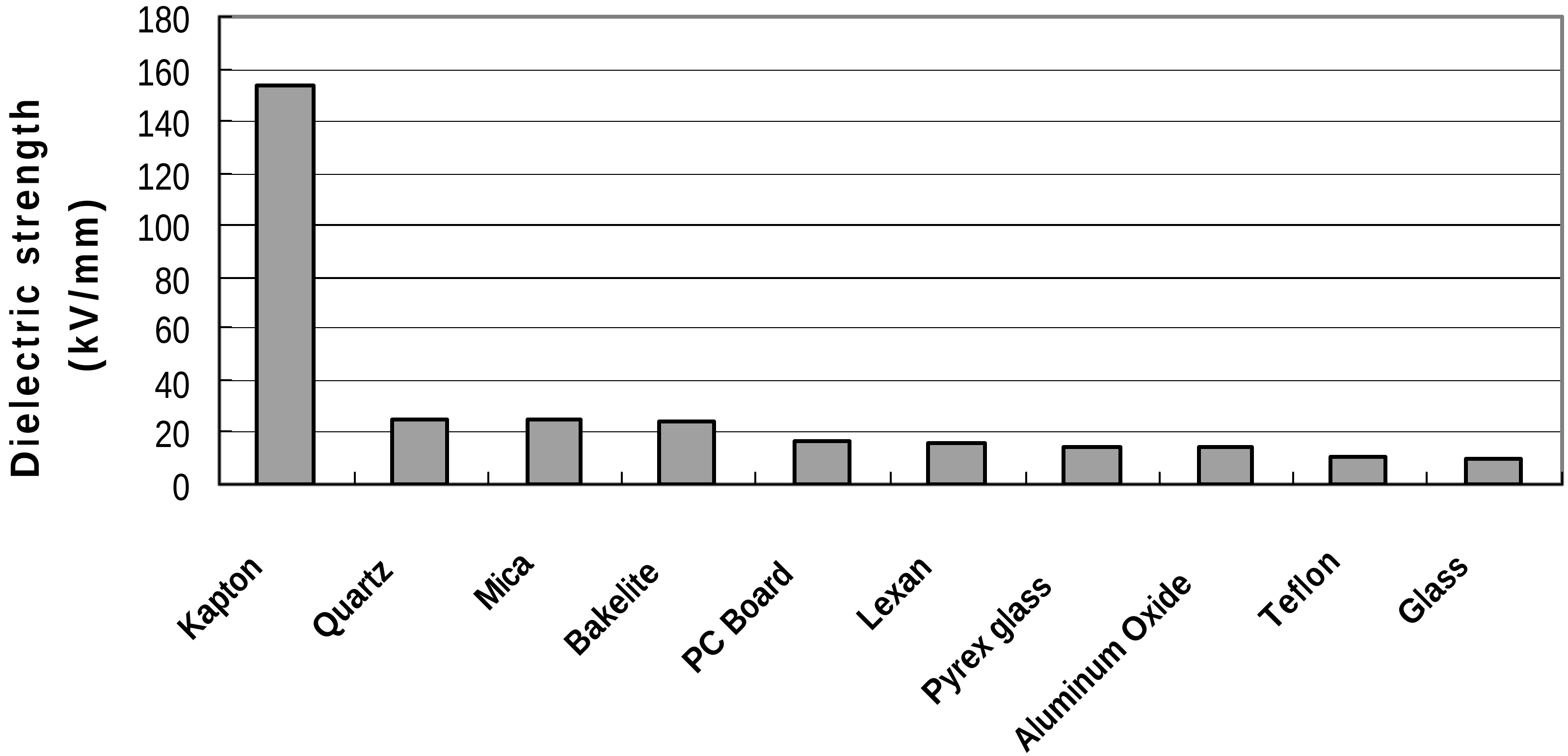


Figure 14 Dielectric strength of candidate actuator materials

DIELECTRIC LOSS FACTOR OF CANDIDATE PLASMA ACTUATOR MATERIALS

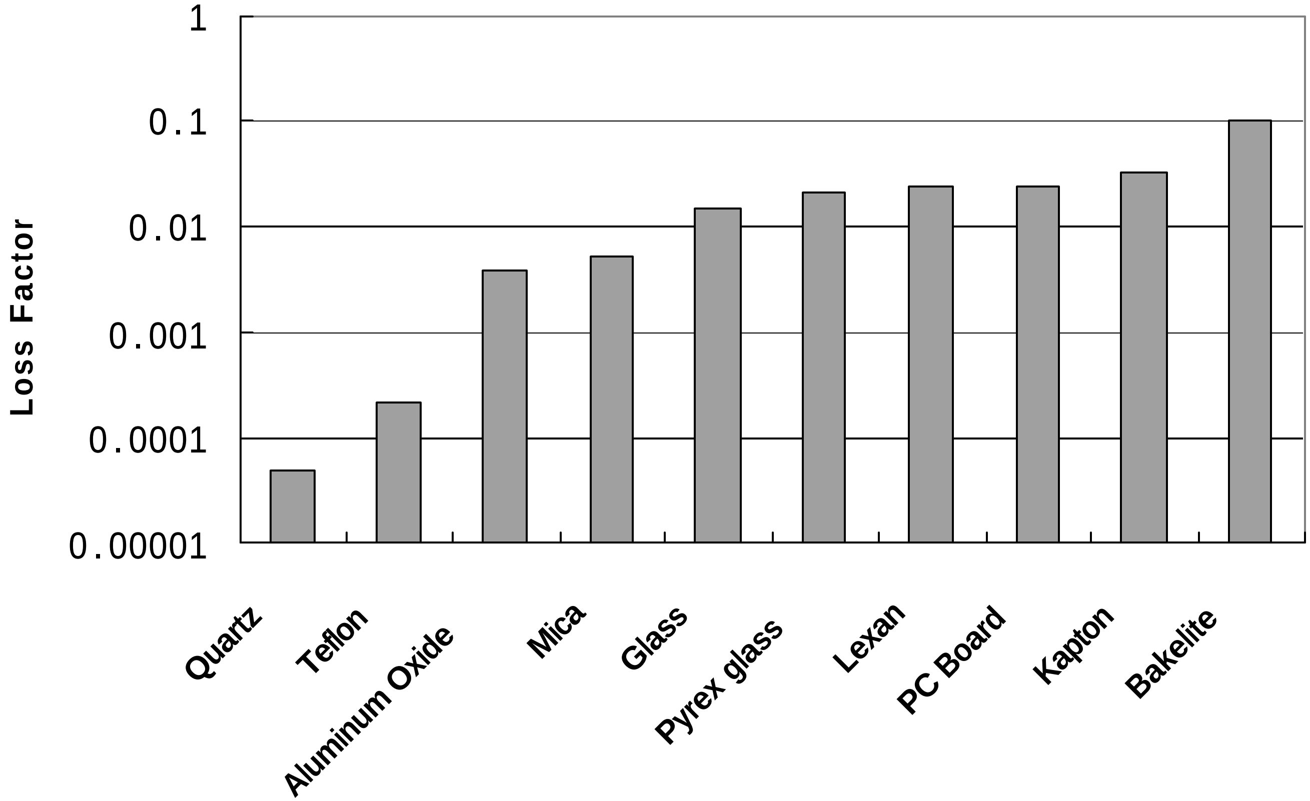


Figure 15. Loss Factor of candidate actuator dielectrics

MASS DENSITY OF CANDIDATE PLASMA ACTUATOR MATERIALS

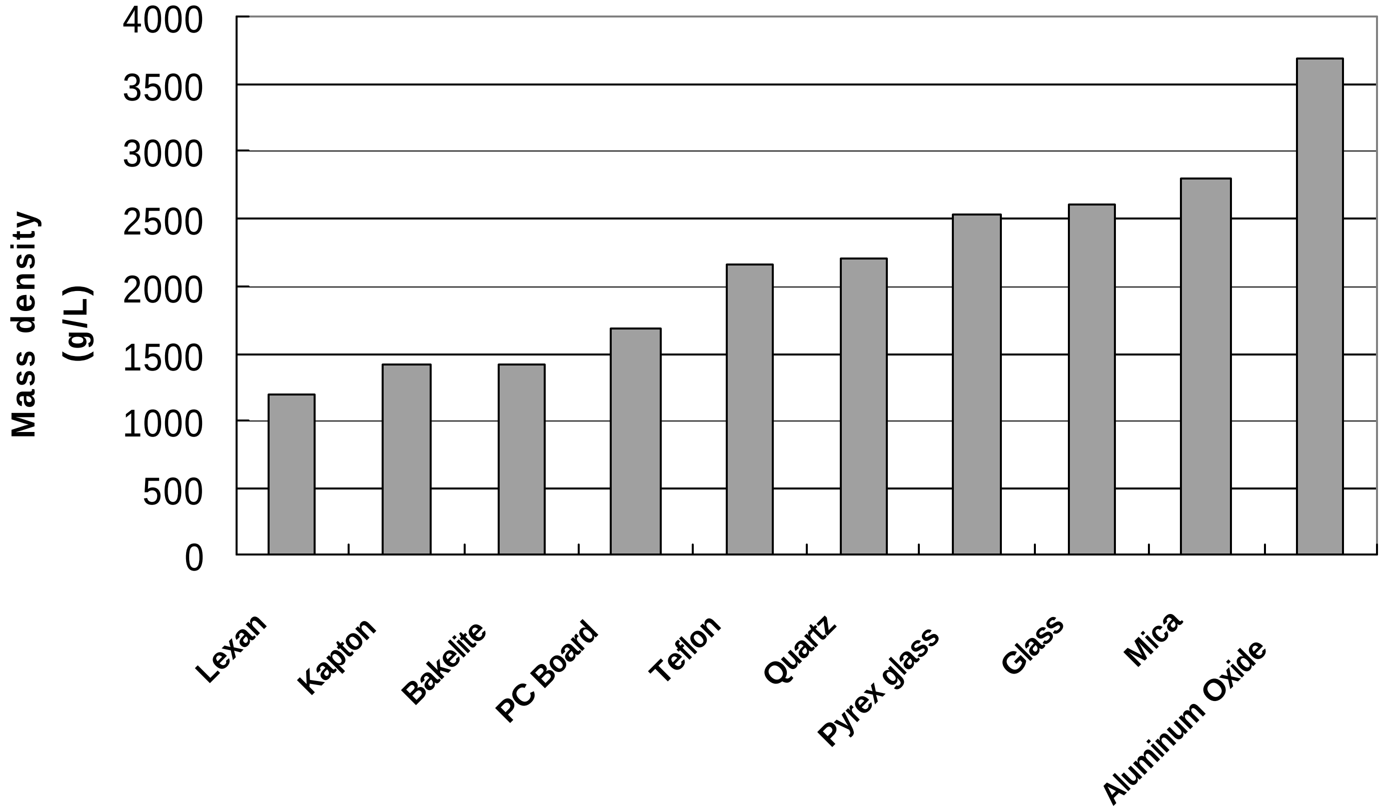


Figure 16 Mass density of candidate actuator dielectrics

INDEX RANK OF CANDIDATE PLASMA ACTUATOR DIELECTRICS

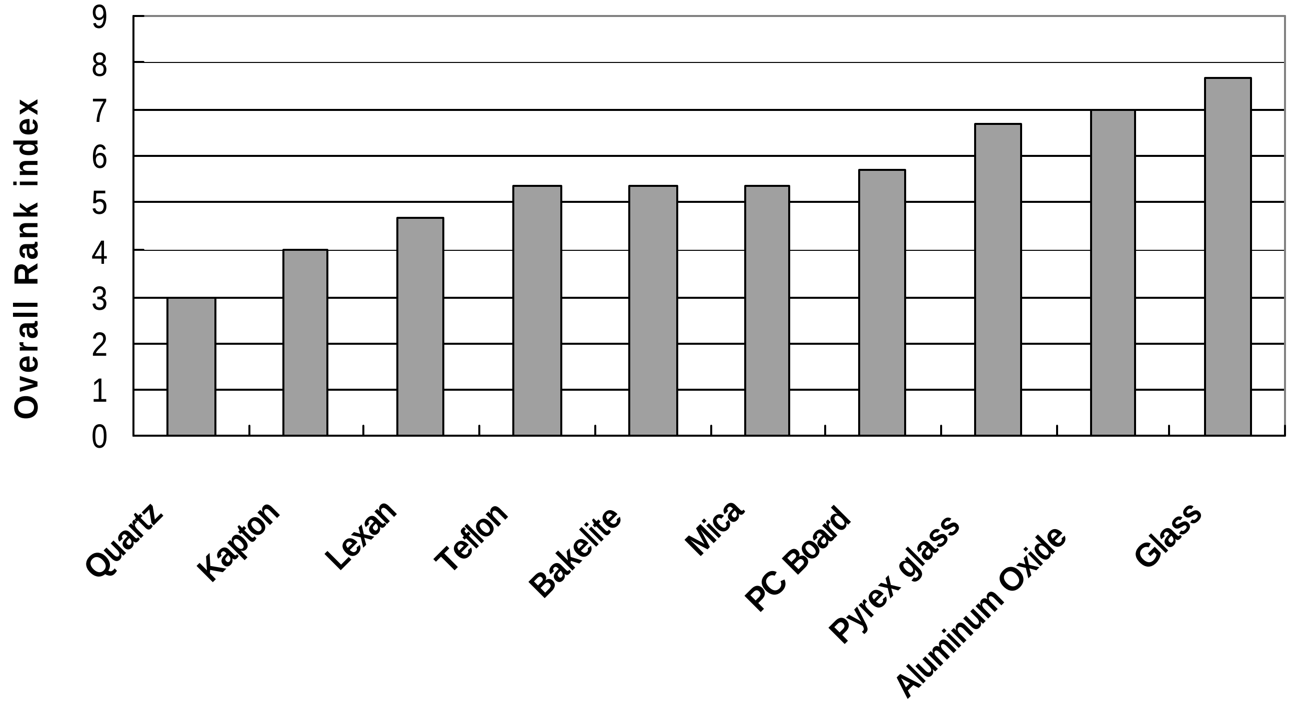


Figure 17 Overall Index rank of candidate actuator materials.

(Overall Index is the average of rank in Dielectric strength, loss factor, and mass density.)

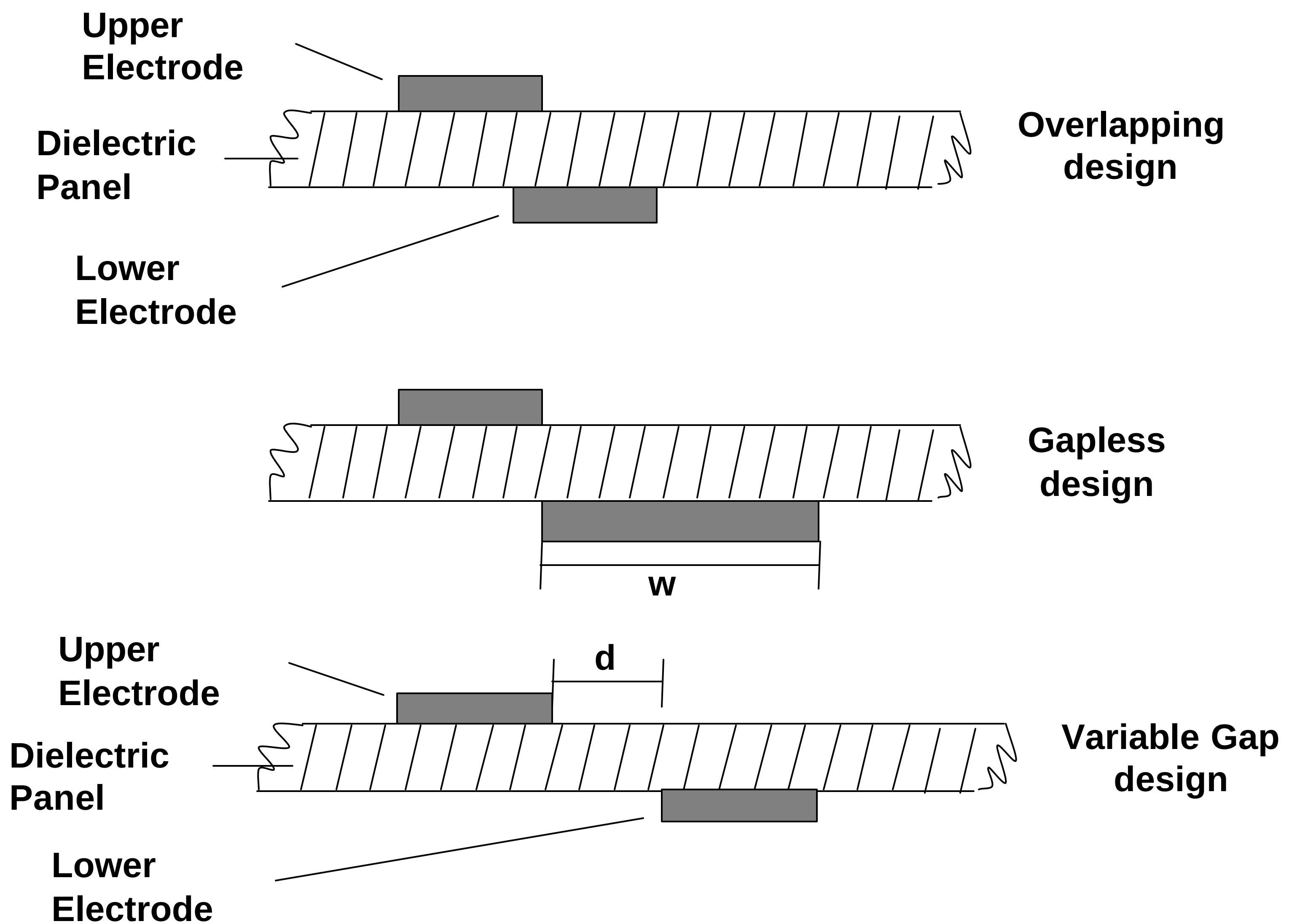


Figure 18 Configurations and optimization parameters of a single actuator

CHARACTERISTICS OF PLASMA ACTUATOR WITH TEFLON DIELECTRIC

Ambient Conditions: 21 ° C, 27% ~ 34% relative humidity
Teflon® PTFE panel 1mm thick, 15 X 15 cm
Dielectric strength: 11.2 kV/mm,
Dielectric constant: 2.1 (1MHz)
Mass density: 2.16 g/cm3

Single electrode (3.18 mm wide) pair, variable horizontal gap, d.

Pitot tube: 15 mm away from top electrode, 1mm above top surface.

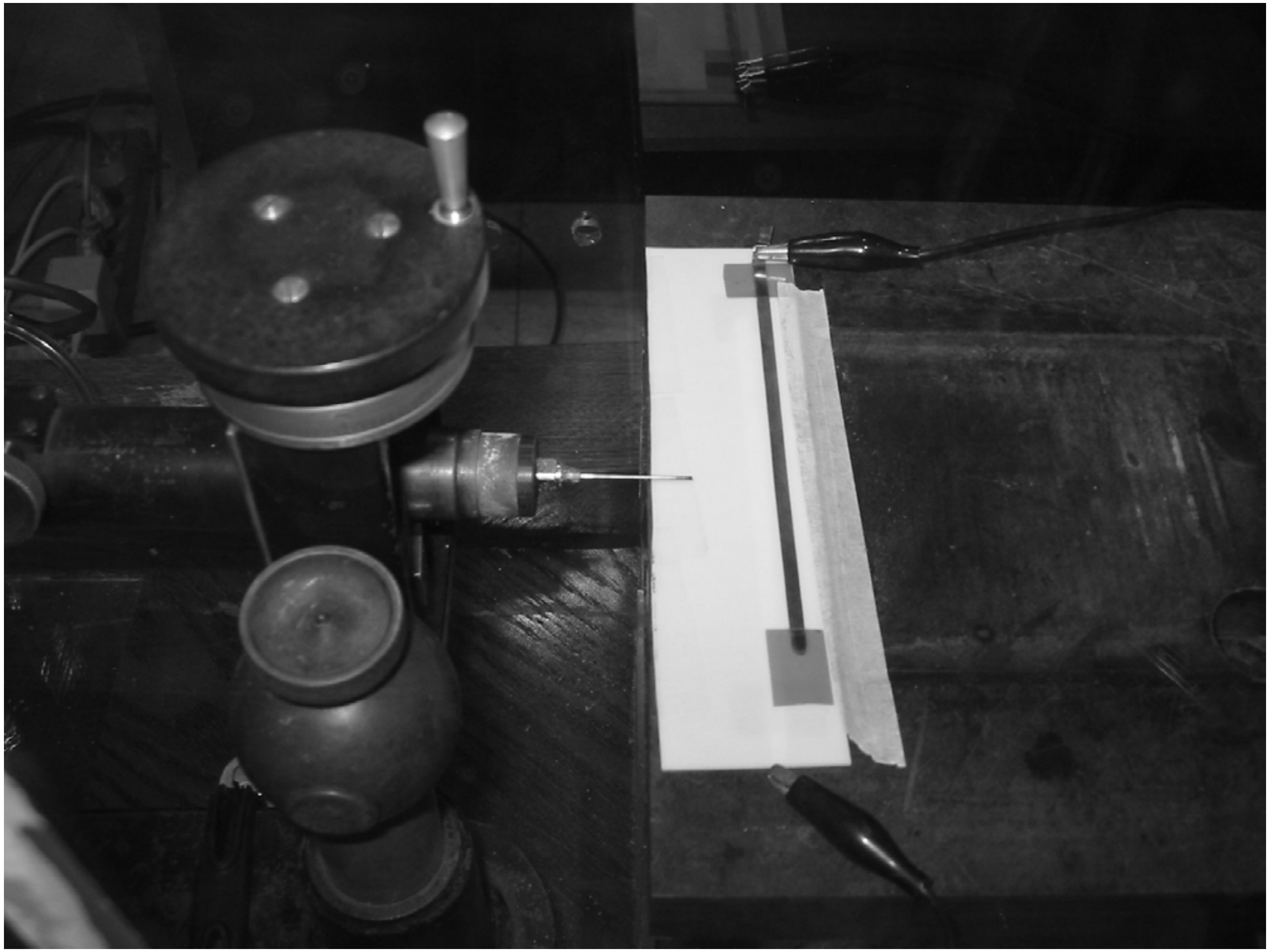


Figure 19 Single plasma actuator on Teflon dielectric with Pitot tube in position.

VELOCITY INDUCED BY A SINGLE TEFLON ACTUATOR AS A FUNCTION OF RF FREQUENCY, RF VOLTAGE AND GAP DISTANCE

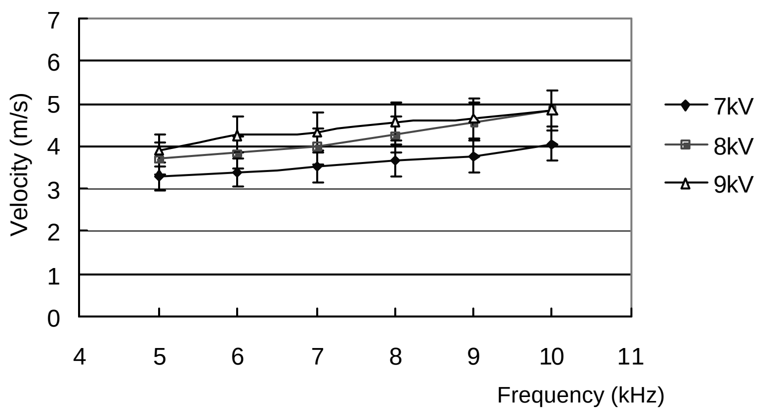


Fig.20a 0mm Actuator

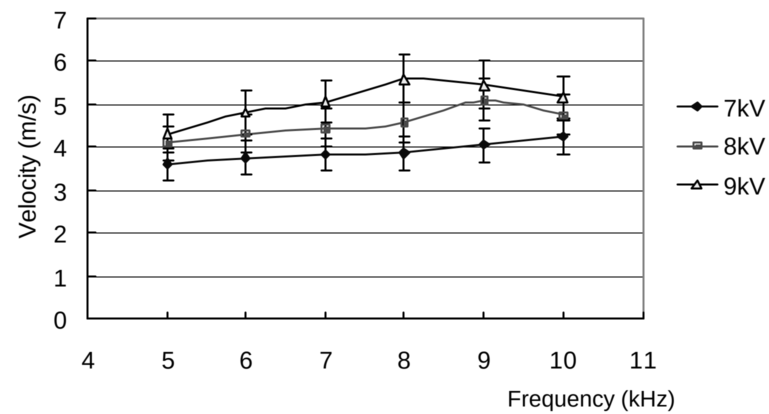


Fig.20b 1mm Actuator

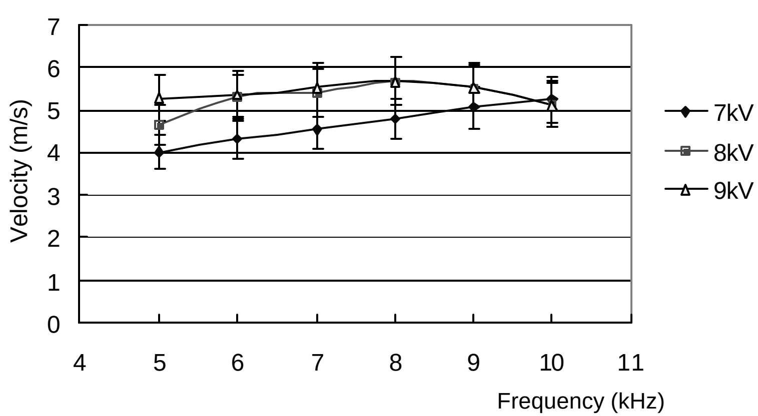


Fig.20c 2mm Actuator

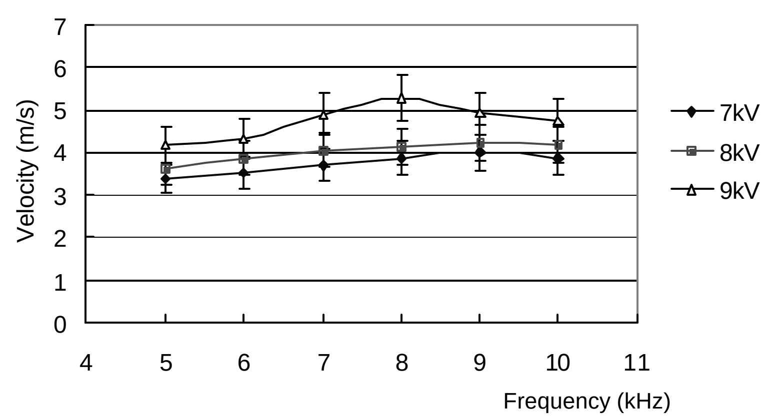


Fig.20d 3mm Actuator

SINGLE ACTUATOR INDUCED VELOCITY AS A FUNCTION OF ELECTRODE GAP DISTANCE AND RF FREQUENCY, FOR VARIOUS RF VOLTAGES

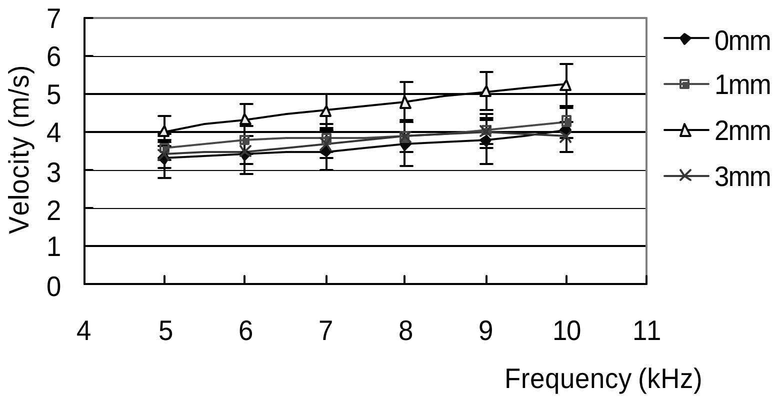


Fig 21a. Single Actuator with various gap at 7kV

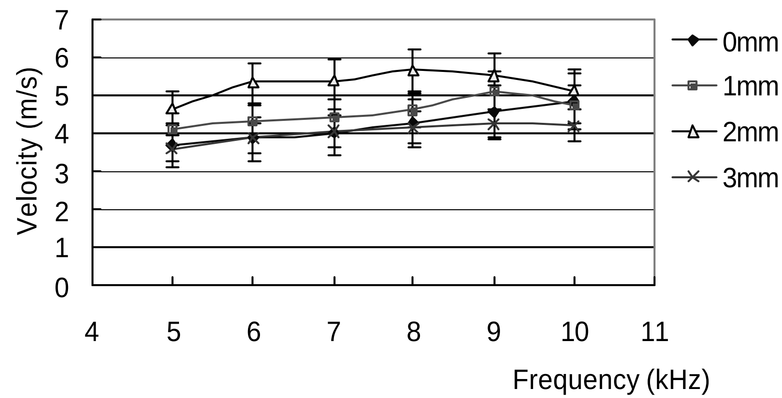


Fig 21b. Single Actuator with various gap at 8kV

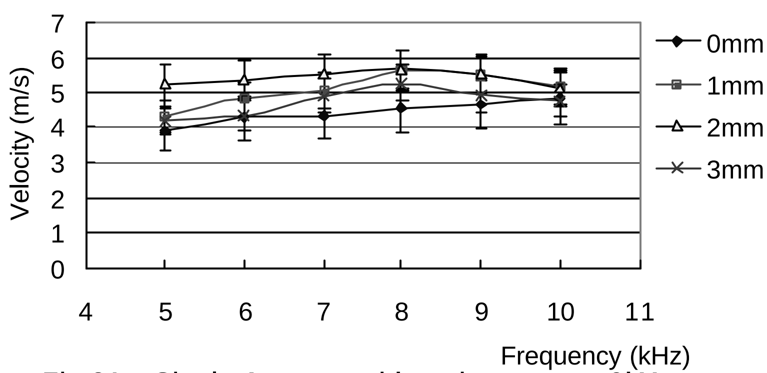


Fig 21c. Single Actuator with various gap at 9kV

SINGLE ACTUATOR INDUCED VELOCITY AS A FUNCTION OF ELECTRODE GAP DISTANCE AND RF VOLTAGE, FOR 8 kHz RF FREQUENCY

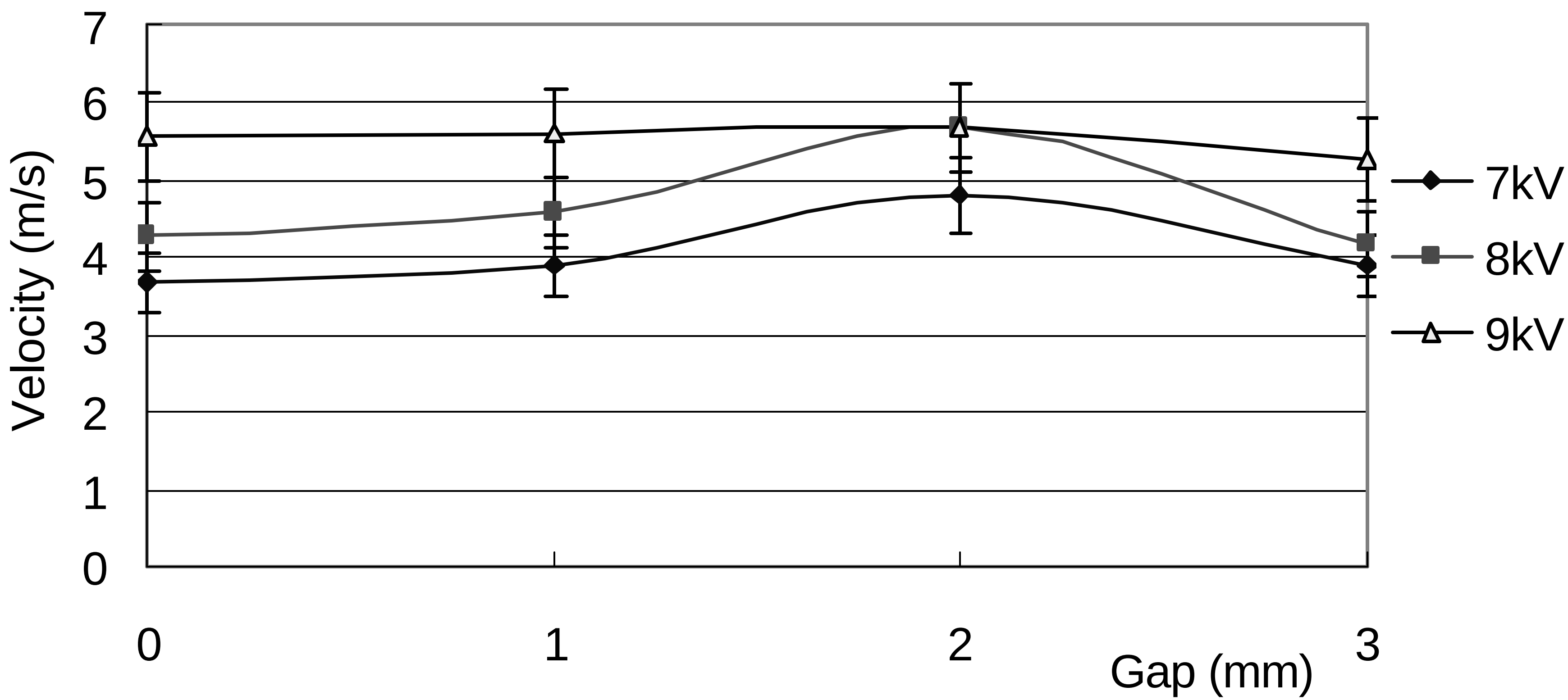


Figure 22. Induced neutral gas velocity as a function of gap distance d and RF voltage for 8 kHz RF frequency.

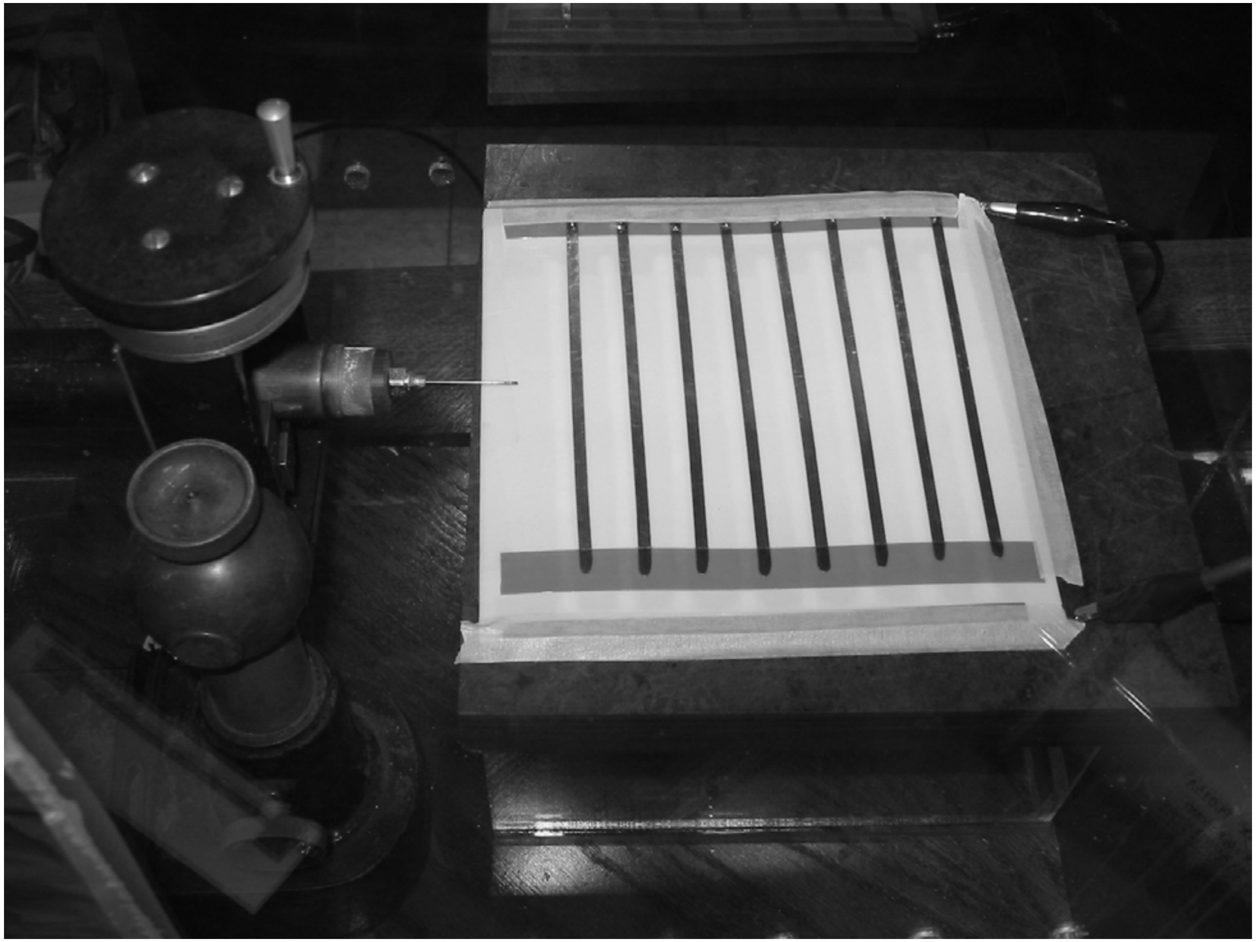


Figure 23 Plasma panel accelerator with 8 actuators and Pitot probe on the left. Pitot tube outer diameter, 0.89 mm; inner diameter, about 0.50 mm.

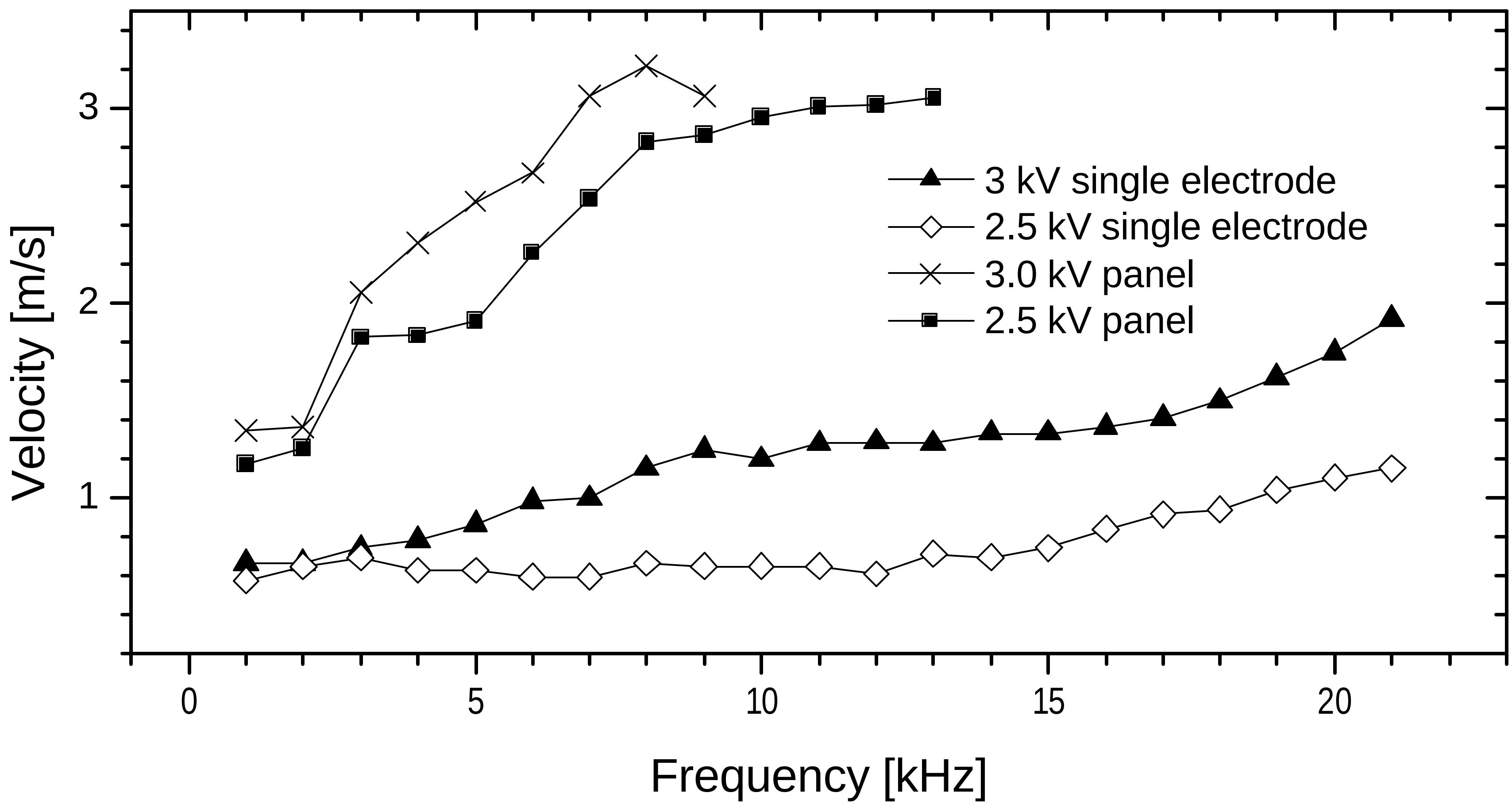


Figure 24. Plasma induced gas flow velocity from Pitot tube data at the RF voltages and frequencies used for the single ceramic actuator of Figure 9 and the 18-actuator ceramic panel of Figures 10 and 11.

CONCLUSIONS

- The real power input to a OAUGDP™ plasma actuator is dissipated both by dielectric heating of the dielectric material between the electrodes, and by power input to maintain the plasma.
- The fraction of the total input power dissipated as dielectric heating ranged from 48% to 100% for a single plasma actuator, and over 27% to 100% for a plasma actuator panel.
- Quartz and Teflon appear to be the most desirable dielectric materials to minimize the power wasted in dielectric heating. Kapton, PC board, and Bakelite are among the worst.
- The induced flow velocity of a single actuator appears to increase with increasing frequency, tracking the net power input to the plasma.
- The induced flow velocity and the net plasma input power to the 18-actuator panel are also strong functions of the RF voltage.
- The induced flow velocity is a function of horizontal gap spacing between electrodes, and a spacing of d = 2 mm appears to be optimum for a single Teflon plasma actuator.
- Induced flow velocities of 5+ m/sec in air have been produced by a single Teflon plasma actuator, and 10+ m/sec in an array of 8 such actuators.

FOR FURTHER INFORMATION:

DOWNLOADABLE PAPERS AND ADDITIONAL INFORMATION ON THE OAUGDPä AND ITS USES MAY BE FOUND AT THE UT PLASMA SCIENCES LABORATORY'S WEBSITE:

http://plasma.ece.utk.edu

INFORMATION IS ALSO AVAILABLE FROM OUR SPIN-OFF COMPANY, ATMOSPHERIC GLOW TECHNOLOGIES, INC.:

http://www.atmosphericglow.com

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