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Work this past year has involved theoretical and experimental efforts directed towards exploiting the use of MHD and plasmas for boundary layer control, the development of a new concept for power extraction from high temperature surfaces, and the development of a new diagnostic for plasmas and high-speed flows. Two control strategies are being examined: the snow-plow arc and the dielectric barrier discharge. The snowplow arc uses a constricted surface discharge which is accelerated by a magnetic field and pushes the air with it. The dielectric barrier discharge uses an electric field gradient along the surface that couples to the flow. Theoretical work has focused on the optimization of both of these concepts for efficient control of boundary layers in high speed flow and on interactions with AFRL on model development and validation. The power extraction concept involves the development of a new pulse sustained thermionic flat panel for extracting power from hot surfaces. The new diagnostic is Radar REMPI, which is based on scattering of microwave radiation from a small laser-induced ionization region in a flowing gas, combusting zone, or plasma. It has the potential for local temperature, velocity, species, and electron density measurements

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STUDIES OF PLASMAS AND MHD INTERACTONS IN SUPERSONIC FLOWS

AFOSR GRANT #FA9550-06-1-0081

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Abstract

Work this past year has involved theoretical and experimental efforts directed towards exploiting the use of MHD and plasmas for boundary layer control, the development of a new concept for power extraction from high temperature surfaces, and the development of a new diagnostic for plasmas and high-speed flows. Two control strategies are being examined: the snow-plow arc and the dielectric barrier discharge. The snowplow arc uses a constricted surface discharge which is accelerated by a magnetic field and pushes the air with it. The dielectric barrier discharge uses an electric field gradient along the surface that couples to the flow. Theoretical work has focused on the optimization of both of these concepts for efficient control of boundary layers in high speed flow and on interactions with AFRL on model development and validation. The power extraction concept involves the development of a new pulse sustained thermionic flat panel for extracting power from hot surfaces. The new diagnostic is Radar REMPI, which is based on scattering of microwave radiation from a small laser-induced ionization region in a flowing gas, combusting zone, or plasma. It has the potential for local temperature, velocity, species, and electron density measurements.

Extended Abstract:

Snowplow Arc

This past year, theoretical work on the snow-plow arc has sought to develop a more thorough understanding of the push work and heat generation, as well as to understand the observed physical attributes of the arc, with the intention of optimizing its potential for boundary layer flow control. In this case, minimization of heating versus push work is the paramount issue. Theoretical analysis shows that the heating can be considerably reduced by operating in a regime dramatically different from that in the early experiments. Equation 1 shows the ratio of the push work to the Joule heat dissipation, where $\mu_{e,i}$ is the average gas velocity of the boundary layer (Eq. 2), E and B are the electric and magnetic field strengths, and Ω_e and Ω_i are the electron and ion Hall parameters.

$$\frac{\text{push work}}{\text{Joule dissipation}} = \frac{u_{e,i}B}{E - u_{e,i}B} \quad \text{(Eq 1)} \qquad u_{e,i} = \frac{u + (E/B)\Omega_e\Omega_i}{1+\Omega_e\Omega_i} \quad \text{(Eq 2)}$$

If the applied electric field is made very weak, close to $E=uB$ (for typical flow conditions $E=10$ to 20 volts/cm), thus making the plasma velocity only slightly greater than the gas velocity, the denominator in Equation 1 is dramatically decreased and efficiency dramatically improved. This electric field is too weak to sustain the plasma, and, therefore, ionization must rely on low duty cycle, high repetition rate short (on the order of a few nanoseconds), high voltage pulses. Through previous work at Princeton these pulses have been shown, to produce high efficiency plasmas. Flow acceleration would occur predominately between the ionizing pulses and substantial acceleration will require strong electric current. Estimates show that the ratio of push work to Joule dissipation (including both dissipation between the pulses and the energy deposited during the pulses) can be increased dramatically from 10^{-2} to approximately 1, while providing velocity increments of $V - V_0 = 40$ to 80 meters per second with magnetic field strengths of 3.2 Tesla and an average conductivity of 2 mho per meter, corresponding to an average electron number density, n_e, approximately equal to 2×10^{12} cm^{-3}. This newly found regime of "slow" magnetically-driven surface discharges looks very promising for boundary layer acceleration.

On the experimental side, collaboration with CMI, Inc. has led to the development of a new sapphire-based, electrode/dielectric element shown in Fig. 1 (bottom inset). This utilizes a titanium copper electrode that is thermally matched to the sapphire, so the unit is robust to heating. Because of the high thermal conductivity of the sapphire it is expected that this will permit higher current densities, and, thus, more efficient coupling to the boundary layer. The device is mounted into a transparent in-draft wind tunnel and inserted into our superconducting magnet. The wind tunnel is currently being instrumented with pressure taps and fitted with a shock generating wedge on the opposite side so the effects of the snow plow arc on shock-induced separation can be observed.

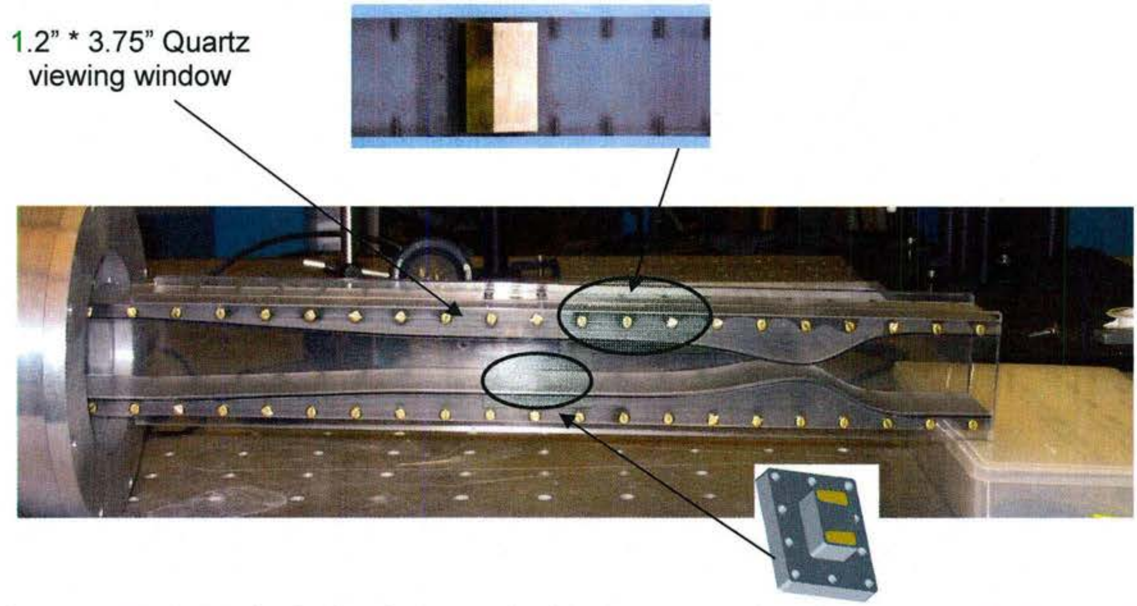

Figure 1: Mach 2.4 in-draft wind tunnel with the test section showing the electrodes and a 10 degree wedge to create a shockwave.

Dielectric Barrier Discharge

There has been much interest in the dielectric barrier discharge configuration shown in Fig. 2. An exposed upper electrode is paired with an insulated electrode located under a thin dielectric and an RF discharge is struck between the two. It has been observed that this discharge generates a surface jet in the direction indicated in the figure. We have undertaken a detailed modeling effort to understand the origin of this surface jet and propose an optimized wave form for increasing the surface jet velocity.

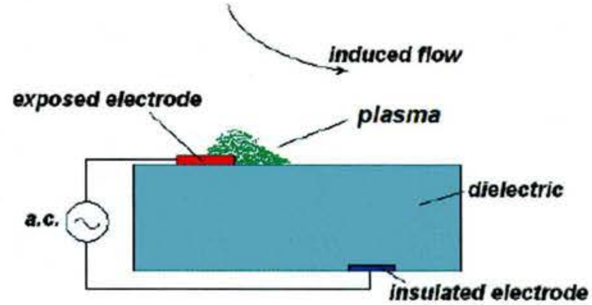

Figure 2. Dielectric barrier discharge configuration

Our modeling indicates that charging of the dielectric occurs during the time the exposed upper electrode is negative, causing a field gradient to be established which subsequently drives the positive ions in the downstream direction. These ions then couple to neutral air and create the jet. The problem with the sinusoidal-varying potential is that there are significant reverse forces that arise.

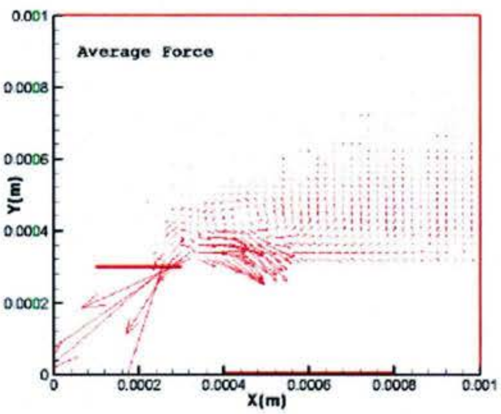

Figure 3. Average forces from a sinusoidal applied voltage

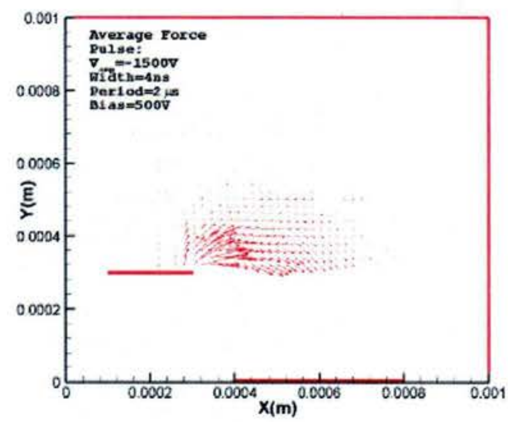

Figure 4. Average forces from a high voltage pulsed applied voltage

Figure 3 shows the average force near the exposed electrode for an applied sinusoidal voltage. From the large-scale, left pointing vectors at the lower-left part of the diagram it is apparent that this reverse force significantly decreases the effectiveness of the device. Our modeling has indicated that, with the application of a very short, negative high voltage pulse to generate the ionization, and a positive DC bias, this reverse effect can be suppressed and a larger average downstream velocity generated, as shown in Fig. 4. The challenge in the modeling and understanding the dielectric varying discharge plasma actuators stem from the physics of the problem. The ability of this new model to capture the important physical phenomena has provided a useful capability for this optimization effort. Work on this program has been jointly supported by Boeing (St. Louis).

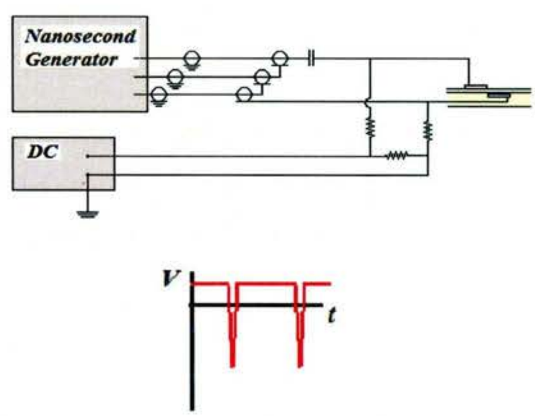

Figure 5: Schematic of pulse generator and DC driven dielectric barrier discharge

A dielectric barrier discharge driven by a nanosecond pulse generator and dc bias, as shown in Fig. 5, has been built. The nanosecond pulse generator is operated in a burst mode in order to provide contrast for Schlieren measurements of the jet created by the dielectric barrier discharge. Figure 6 shows an asynchronous movie of the jet generated by the dielectric barrier discharge. The frames proceed from top-to-bottom, left-to-right. The velocity of the structures is on the order of 25 m/sec, increasing by almost a factor of two with the DC bias. This diverging structure is driven by the small-scale surface jet in proximity to the barrier discharge. That jet will have much higher velocity then this large-scale downstream structure. Work is on-going to measure that velocity and (with Dr. Jon Poggie at AFRL) to development parallel architectures for the code and expand the code capabilities.

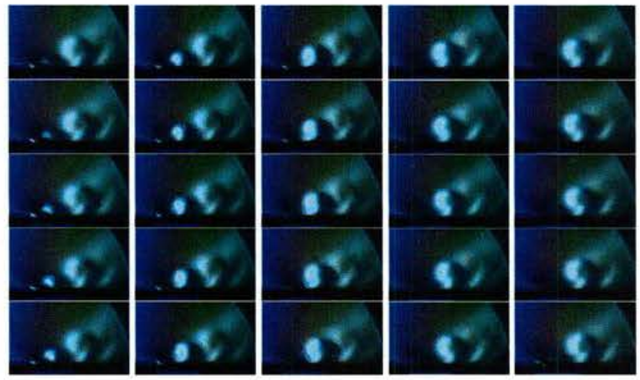

Figure 6: Asynchronous shadowgraph images of the pulsed DBD surface jet . Frames are top to bottom, left to right.

Thermionic Power Conversion

Large temperature gradients occur between surfaces exposed to high temperatures associated with engines and/or high speed flight and the structure elements that support those materials. It would be attractive to find a way of converting a significant portion of that heat into electricity, not only for applications on board a vehicle, but also for augmenting cooling. For modeling work undertaken during the past year, we believe that an efficient two-dimensional thermionic panel can be built and operated with an internal plasma sustained by high voltage pulses.

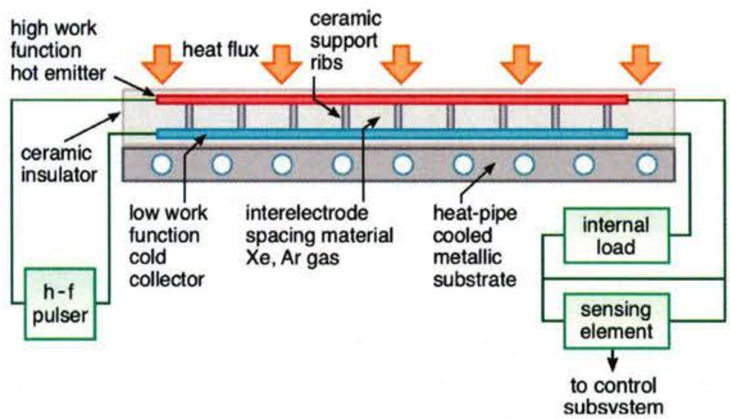

Figure 7: Diagram of thermionic surface panel for power extraction and enhanced cooling

Two types of thermionic devices have been previously examined: a narrow gap configuration and a cesium vapor-filled ignited mode configuration. In the first case, to avoid significant current reduction by space charge build-up, very small interelectrode gaps on the order of a few microns are required. These are impractical for structural elements, however, recent work on nanoscale thermionic devices may provide some new capabilities in this area. More commonly, space charge is overcome by a discharge that is sustained in few millimeter interelectrode gap filled with cesium vapor. Cesium is chosen because of its low ionization potential, but it adds complexity to the configuration since the vapor pressure of the cesium must be controlled by a low temperature reservoir that may not be easily incorporated into an extended panel configuration. The use of an inert gas together with high voltage pulses relieves the need for a low temperature reservoir and opens up the opportunity for a two-dimensional device. A diagram of such a device is shown in Fig. 7. Figure 8 shows the power expended in the generation of electrons for 1000 K argon at various pressures in a 5 mm gap device. This power is sufficient to sustain 10 amps/cm^2 of current, and, averaged over the pulse repetition rate, corresponds to only a few percent of the power generated by the device itself. Because of the small separation between electrodes, the high voltage pulses only correspond to voltages of a few tens of volts. Experimental work is planned over the next year with additional support from the Air Force Research Laboratory.

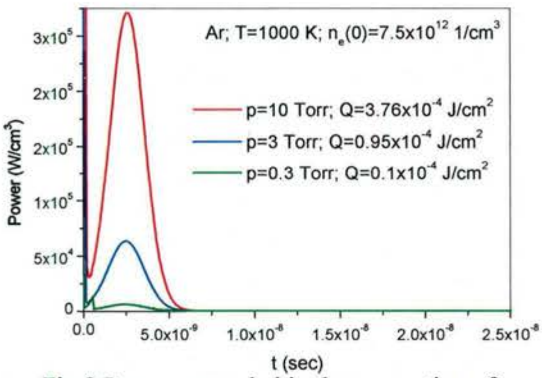

Fig.8 Power expended in the generation of electrons in the gap by high field, nanosecond pulse.

Radar REMPI

We have undertaken the development of a new diagnostic approach based on the scattering of microwave radiation from a small laser-induced plasma. The laser is tuned to a wavelength that produces a very small plasma through resonant-enhanced, multiphoton ionization, and this plasma is observed by microwave scattering. Due to the high sensitivity of the microwave detection and its direct relationship to the density of charges, the whole lifecycle of the laser-induced plasma can be measured from the initial stages of ionization during the nanosecond laser pulse, through the growth of the spark evolution, and finally the loss of charge through recombination and attachment. The resonant-enhanced nature of the laser-generated ionization provides the capability of using this technique for spectroscopy by frequency tuning the laser. By observing the rate of recombination, particularly for very weak sparks, this approach may provide a new method for the measurement of temperature. Of particular interest for this work is the potential for using the rise time of the pulse to determine the ambient electron number density. The geometry of the scattering is shown in Figure 9. Modeling of a true laser pulse indicates that the electron number density increases in an exponential fashion during the rise time of the laser pulse, reaching significant ionization in a time related to the initial electron number density and the fluence of the laser. Figure 10 shows the different rise times associated with different laser pulse energies all focused to the same focal volume. By observing the time between the initial turn-on of the laser pulse and the observation of the microwave scattering, it may be possible to extract the initial electron number density. Work is currently on-going to examine this possibility.

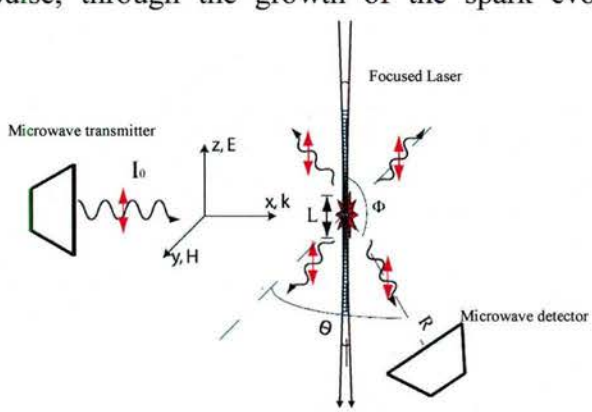

Figure 9: Radar REMPI configuration

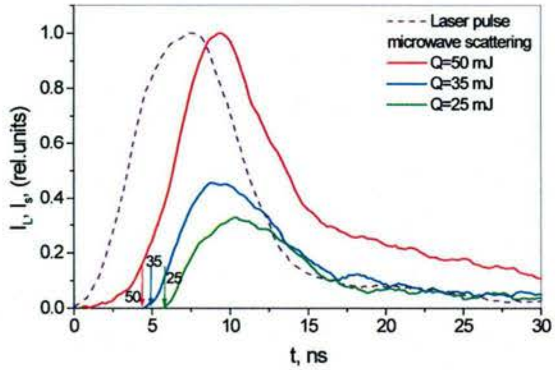

Figure 10: Measured Radar REMPI signal in air at pulse energies showing the delay in rise time associated with pulse energy. Arrows are from Figure are predictions based on the laser pulse shape.

Acknowledgment/Disclaimer

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Publications (2006)

R. C. Murray, S.H. Zaidi, and R. B. Miles, "Magnetohydrodynamic Power Generation Using Externally Ionized, Cold, Supersonic Air as a Working Fluid", AIAA Journal, 44 (1),: Jan 2006, pp 119-127.

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W. Beck, E. Stockman, S. Zaidi, and R. Miles, "Rayleigh Scattering Measurements for Obtaining Spatially-Resolved Absolute Gas Densities in Large-Scale Facilities," AIAA-2006-835, AIAA 44th Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 9-12, 2006.

S. Macheret, "Physics of Magnetically Accelerated Nonequilibrium Surgace Discharges in High Speed Flow" AIAA-2006-1005, AIAA 44[th] Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 9-12, 2006.

S. Zaidi, T. Smith, S. Macheret, and R. Miles, "Snowplow Surface Discharge in Magnetic Field for High Speed Boundary Layer Control," AIAA-2006-1006, AIAA 44[th] Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 9-12, 2006.

Likhanskii, M. Shneider, S. Macheret and R. Miles, "Modeling of Interaction Between Weakly Ionized Near-Surface Plasmas and Gas Flow," AIAA-2006-1204, AIAA 44[th] Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 9-12, 2006.

Z. Zhang, M. Shneider, S. Zaidi, and R. Miles, "Microwave Diagnostics of Small Volume Laser-Induced Plasma," AIAA-2006-1357, AIAA 44[th] Aerospace Sciences Meeting and Exhibit, Reno, Nevada, Jan. 9-12, 2006.

Z. Zhang, M. Shneider, and R. Miles, "Diagnostics by RADAR REMPI: Microwave Scattering from Laser-Induced Small Volume Plasmas", AIAA-2006-2971, 25[th] AIAA Aerodynamic Measurement Technology and Ground Testing Conference, San Francisco, CA, June 5-8, 2006

S.O. Macheret, M.N. Shneider, and R.B. Miles, "Modeling of Thermionic Devices with Plasmas Sustained by Repetitive Pulses", AIAA-2006-3385, 37[th] AIAA Plasmadynamics and Lasers Conference, San Francisco, CA, June 5-8, 2006

Honors & Awards Received

Richard Miles elected to the Executive Committee for the International Liaison Group for MHD

AFRL Points-of-Contact: Jon Poggie, Roger Kimmel, Datta Gaitonde. Additional interactions with Jim Gord, Campbell Carter, Skip Williams, Alan Garscadden, Robert Mercier, Ron Kerans, Daniel Risha, and many others. Seminars given at AFRL on June 19 and 20, 2006.

Transitions

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Phase II (DARPA SBIR) (load bearing MHD structure with embedded magnet)
Phase I and Phase II (AFOSR STTR) (surface plasma control device)
Research Support Instruments 11 Deer Park Dr., Suite 124, Monmouth Junction, NJ 08852, Phone: (732) 329-3700) contact: Dr, John Kline kline@researchsupport.com
Phase II (AFOSR STTR)(Microwave enhanced combustion)
Phase I (AFOSR STTR) (Nitric oxide detection)

New Discoveries: provisional patents filed for

- **"Doppler Radar REMPI" Richard B. Miles**
- **"Externally Ignited Thermionic Power Converters and their use as Cooling Surfaces for Hypersonic Vehicles and Internal Ram/Scram Engine Walls", Richard B. Miles, Mikhail N. Shneyder, Craig A. Steeves, Sergey O. Macheret**