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The Nonequilibrium Thermodynamics Laboratories (NETL) at the Ohio State University are conducting this research program into the physics of high energy air flows. The particular environments being studied are gas flows in which large amounts of energy are stored internally in the flow molecules, although the gas temperatures remain relatively cold. Such environments occur in hypervelocity aerospace vehicle flow fields, notably behind the bow shock wave in front of the vehicle, and in the after-body expansion and the rocket exhaust expansion flows behind the vehicle.

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**Energy Transfer Processes Among Electrons and Vibrationally Excited  
Air Species in High Enthalpy Flows**

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## 2. Abstract:

The Nonequilibrium Thermodynamics Laboratories (NETL) at The Ohio State University are conducting this research program into the physics of high energy air flows. The particular environments being studied are gas flows in which large amounts of energy are stored internally in the flow molecules, although the gas temperatures remain relatively cold. Such environments occur in hypervelocity aerospace vehicle flow fields, notably behind the bow shock wave in front of the vehicle, and in the after-body expansion and the rocket exhaust expansion flows behind the vehicle. The mechanisms and specific rates of several of these energy transfer processes have been determined in the present program. There are further applications to ionized gas flows which are of importance in combustion flows, in electrical rockets and in plasma aerodynamic control. Another environment of increasing USAF importance is supersonic flows of air and other gaseous molecules in high power gas lasers being developed for DED of AFRL. Such supersonic flow lasers are being developed at NETL under related USAF programs, and critical energy transfer mechanisms in the laser are being studied under the present research program.

## 3.1 Research Highlights:

### Storage and Transfer of Vibrational Energy in Supersonic Flows

In high speed flows, a considerable fraction of the flow energy can be “frozen” in the internal vibrational motion of the gas molecules. The storage and transfer of this energy with the external modes of molecular motion (translation, rotation) exerts a major influence on the flow field temperature, heat transfer rates, and the position of bow shocks on reentry vehicles. Further, in expansion flows, such as rocket exhaust plumes, energy transfer of this type can strongly influence the radiation emitted from the exhaust, and, as such, is important in plume signature detection. Work this year at The Ohio State University has resulted in measurements of the rate of vibrational mode energy transfer among the major air species, nitrogen and oxygen. Notably, the specific rates of such energy transfer have been measured as functions of initial vibrational energy state for both these species. There have also been similar measurements for other diatomic species, including hydrogen, carbon monoxide, and nitric oxide. Related work in a supersonic wind tunnel, operating at Mach 3 velocity, with a substantial fraction of the flow energy frozen in nitrogen vibration, has demonstrated for the first time the deceleration of a cold supersonic flow by the direct application of an electromagnetic force (Lorentz force). The flow velocity was reduced by approximately 5%.

Fig. 1 below gives the measured specific rates of vibrational energy transfer between two oxygen molecules, one in an excited vibrational quantum state (quantum number “ $v$ ”) and the other in the ground vibrational quantum state ( $v=0$ ), before collision. The experimental OSU rates are shown, together with those theoretically predicted for this process by the semi-classical scattering theory of C. Coletti and G. D. Billing (Chem. Phys. Lett. V. 356, p. 14 (2002)). It can be seen that the measured rates are considerably faster than those predicted. However, if the attractive force between molecules is increased by approximately 175 %, the theory is in quite reasonable correspondence with both the measured magnitude and quantum-number dependence.

### Measurement of Electron Attachment and Recombination in Low Temperature Air

New data for the rates of electron removal in cold air plasmas, and for related energy transfer mechanisms, have been obtained. Most notably, a method to dramatically decrease the rate of electron removal in cold air plasmas has been further developed. A paper on this work, AIAA Paper No.2005-2257 “Mitigation of Oxygen Attachment in High Pressure Air Plasmas by Vibrational Excitation” was named in 2005 as recipient of the AIAA Best Paper by the AIAA Plasmadynamics and Lasers Technical Committee. This work may well lead to efficient means to create improved lasers and plasma aerodynamic devices for USAF. Fig. 2 below illustrates this key result. Dry air, in a cell at atmospheric pressure and room temperature, is ionized by a pulsed electron beam. A laser is used to excite the vibrational modes of the air molecules. The electron number density,  $n_e$ , measured by microwave absorption, is plotted against time.

With no vibrational excitation ("laser off" case), the ionization produced by the electron beam is small, and the plasma rapidly decays when the electron beam is turned off. With the laser on, and high levels of vibrational excitation shown are maintained, not only is the free electron density greatly increased, but the plasma lifetime increases by more than  $10^2$ . As discussed in recent papers on this development, the increase in electron density and plasma lifetime are actually due to acceleration of electron detachment from molecular oxygen by the effect of oxygen vibrational excitation. It should also be noted that maintenance of a free electron density of  $\sim 10^{13}$  electrons/cm<sup>3</sup> by the electron beam alone requires  $\sim 2$  kW/cm<sup>3</sup> power input; maintenance of this plasma ionization level with the vibrational excitation technique requires only  $\sim 50$  W/cm<sup>3</sup>, even allowing for the power input of both the electron beam and the pump laser.

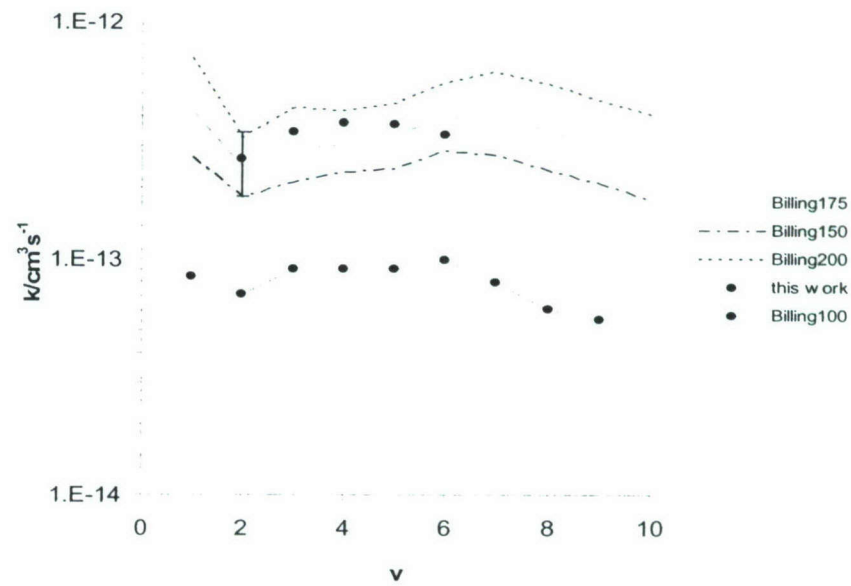


Fig. 1. Oxygen V-V Rates

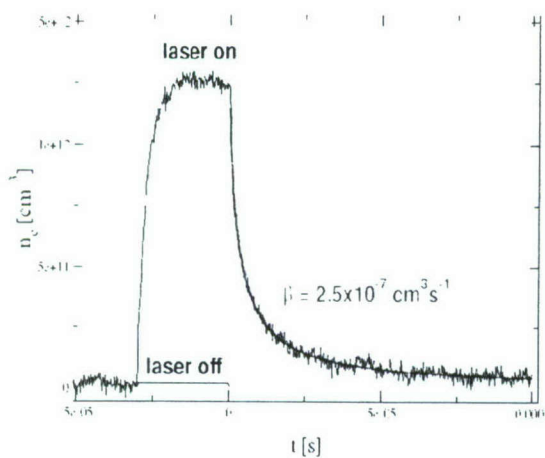
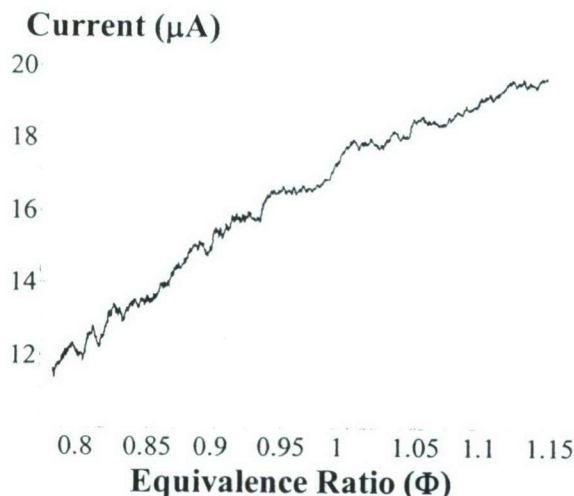


Fig. 2. Mitigation of Electron Attachment in Air



## Development of Thomson Electron Density Probes for Combustion Flows



In this phase of the program, a test combustor has been developed, which exhausts into a small supersonic nozzle. The combustor, in the plenum of the supersonic nozzle, burns mixtures of air and gaseous hydrocarbon fuels; the exhaust products are expanded to  $M = 3$  in the nozzle. Electrodes on opposing sides of the nozzle wall are biased with a small voltage potential, and the current produced from chemionization electrons is measured (a "Thomson probe"). From this measurement, the electron density in the exhaust flow reaction products is inferred. The probe can also be used to remove almost all the free electrons from the flow. The probe is being used to investigate the effect of free electrons on the chemiluminescent radiation intensity in the supersonic exhaust, and to determine the utility

of measurement of combustion efficiency in this type of reaction product supersonic exhaust.

**Fig. 3** above shows the chemi-ionization current measurement against the equivalence ratio of the oxidizer / fuel mixture. The oxidizer used is  $O_2 / Ar$  mixture and the fuel used was  $C_2H_4$ .

The fuel is injected just upstream of the combustion chamber, which also serves as a plenum for a converging/diverging  $M = 3$  nozzle. To control and monitor the amount of fuel injected, we inject the fuel through a thin choke plate and measure the pressure upstream of the choke. Thus we can accurately measure and calculate the amount of fuel we are putting in. In these runs, as the current was being measured by an oscilloscope, fuel concentration was changed by a controlling valve. We saw an almost proportional change in chemi-ionization current. Work is continuing to develop these probes as a combustion-monitoring diagnostic, as well as to investigate applications to exhaust flow radiation control.

### 3.2 Relevance/Transitions

We enumerate the basic successes in our AFOSR program over the last few years, and how they will (and are) impacting Air Force Systems:

1. The production of new experimental and theoretical data for the rates of transfer among specific vibrational states of various air and combustion exhaust species, notably  $O_2$ ,  $N_2$ ,  $CO$ , and  $H_2$ . These data are being incorporated into modeling codes for hypervelocity flows, notably at AFRL Air Vehicles Directorate, Propulsion Directorate, and Directed Energy Directorate; these rates are also beginning to be used by some USAF contractors in their modeling codes.
2. The development of techniques to inhibit the decay rate of weakly ionized air and oxygen-containing plasmas operating at high pressures and low temperatures. Coupled with these techniques, advanced methods have been developed to sustain large volume electric discharges in high velocity air flows at low temperatures. These results have enabled the following systems developments to be initiated:
  - a) Electric-discharge-excited oxygen-iodine lasers, for Joint Technology Office and AFRL DED. Programs are underway at Ohio State, CU Aerospace and U. of Illinois, and at Kirtland AFB.
  - b) The development of supersonic magnetogasdynamic wind tunnels, operating at low gas temperatures in unseeded air flows. OSU is currently operating one of the only two such tunnels in the United States, under programs funded by Air Vehicles Directorate and by

the Unsteady Aerodynamics and Hypersonics Program of AFOSR. In recent work at Ohio State, these programs have demonstrated obtaining major boundary layer turbulence modification in a supersonic flow, and, very recently, direct deceleration of a supersonic nozzle flow by imposing an electromagnetic field on the flow.

- c) The development of a cold plasma ignition system for aerospace combustors. Under sponsorship by Propulsion Directorate of AFRL, and from the Propulsion Program in AFOSR, NETL has developed a method of igniting low temperature hydrocarbon/air mixtures at temperatures and equivalence ratios far outside normal ignition limits. Applications to scramjet igniters and high altitude re-start are being considered; work is being done in collaboration with industrial firms, including GE engines, ISSI, and PSI, under SBIR and STTR programs.
3. The discovery and elucidation of mechanisms governing energy transfer from highly excited molecular quantum states to fast-radiating electronic states of various air and combustion species. OSU NETL have found that removal of free electrons from the flow can inhibit the energy transfer and subsequent visible radiation. This process is presently being studied in realistic supersonic combustion exhaust flows. There is as yet no systems application under study. However, if these mechanisms are found to be operative in plume flow fields, applications to signature masking are an attractive possibility.
  4. Recognition of recent OSU achievements must be noted as part of any "success story." We cite only two of these, occurring in the past two years under the program:
    - a) The past *two* Decembers, "Aerospace America" magazine, the semi-popular monthly of the American Institute of Aeronautics and Astronautics, in its "year-in-review" issues, citing all major advances in aerospace science and engineering, has featured many of the OSU results mentioned above in considerable writeups, with photographs, as major advances in the "plasmadynamics and lasers" technical area. We have recently been asked by the Thermophysics Technical Committee to report, for a third year, on our more recent results in the 2006 "year-in-review" issue. This has been submitted.
    - b) In the recent AIAA Aerospace Sciences Meeting in Reno, NV in January, J. William Rich presented an invited one-hour review of many of the basic kinetic rate results achieved under the current and previous AFOSR programs. Various engineers from NASA, USAF, and other aerospace agencies are requesting this paper and the published information from the program.

#### **Publications**

1. S. Keshav, Y.G. Utkin, M. Nishihara, A. Bao, J.W. Rich, and I.V. Adamovich, "Studies of Chemi-Ionization and Chemiluminescence in Supersonic Flows of Combustion Products", accepted for publication by *Journal of Thermophysics and Heat Transfer*, 2007
2. I.V. Adamovich and J.W. Rich, "Emission and Shock Visualization in Nonequilibrium Nitrogen Afterglow Plasma", *Journal of Applied Physics*, vol. 102, 2007, p. 083303
3. T. Ahn, I. Adamovich, and W.R. Lempert, "Stimulated Raman Scattering Measurements of H<sub>2</sub> Vibration-Vibration Transfer", *Chemical Physics*, vol. 355, 2007, pp. 55-68
4. K. Frederickson, W. Lee, P. Palm, I.V. Adamovich, J.W. Rich, and W.R. Lempert, "Mitigation of Electron Attachment to Oxygen in High Pressure Air Plasmas by Vibrational Excitation", *Journal of Applied Physics*, vol. 101, 2007, p. 093302