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Energy conversion in high enthalpy flows and non-equilibrium plasmas

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ABSTRACT

Recent developments in the study of very high energy non-equilibrium fluid flows are reviewed. These are flows of molecular gases which exhibit substantial degrees of mode disequilibrium, specifically high energy in molecular vibrational and electronic modes, and high electron energies when the gases are weakly ionized. In contrast, the modes of molecular translation and rotation remain at lower energies. Attention is focused on high density, collision-dominated gases. Studies in two systems are presented: A small wind tunnel where an $M=5$ steady air flow over small models is produced, and a flowing carbon monoxide gas laser, exhibiting very high energy loading of the vibrational quantum states. The development of non-intrusive optical diagnostics to measure vibrational and electronic state populations and rotational/translational mode temperatures in the flows, with high spatial and temporal resolution, is presented. Kinetic modeling and experimental validation studies in these environments are also discussed.

1. Introduction

The nonequilibrium of molecular modes of motion can play a major role in high speed flow fields, influencing dynamic forces, heat transfer, and radiative signatures in aerospace vehicles. In addition, such flows often are weakly ionized plasmas, with attendant electron-molecule energy transfer processes that figure in the study and development of high power gas lasers. Non-equilibrium is defined here as occurring in a fluid when one or more molecular or electron components have differing mean energies. Usual thermodynamic equilibrium does not pertain; the fluid energy content cannot be characterized by a single temperature. Such non-equilibrium can be created by a variety of processes, including shock heating, rapid supersonic expansion, radiative energy absorption, or the passage of an ionizing voltage pulse. If the fluid is isolated from further work interactions, the system will of course decay ("relax") to thermal equilibrium, but with continuing rapid energy input, quasi-steady state non-equilibrium can be maintained.

The Non-equilibrium Thermodynamics Laboratories (NETL) at Ohio State conduct studies of a variety of non-equilibrium flows of particular aerospace interest. Of special interest are weakly-ionized environments where the slow-relaxing vibrational energy modes and the free electrons have much higher energies than the translational and rotational modes of flowing gases. We review here two on-going projects involving such environments. The first is basic study in a small scale Mach 5 non-equilibrium flow wind tunnel. In the tunnel, the vibrational energy of air species is loaded by an electric discharge in the plenum, and the energy content is controlled by adding relaxer species downstream. The second project is an application of non-equilibrium flow studies. This project is to extract power from a hypersonic air flow reacting with carbon at high altitude. This involves the development of a high power laser using carbon monoxide produced by reacting entrained air with carbon. The laser is to develop a total population inversion among its vibrational quantum states.

2. Nonequilibrium flow wind tunnel experiments

The wind tunnel is a small scale supersonic flow system, which can develop steady Mach 5 flows that can be sustained for several seconds. Turn-around times are short, enabling many test runs to be made each hour. With the non-equilibrium loading of the molecular vibrational modes, these are actually very high enthalpy flows, an environment which is usually achieved only in short

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duration hypersonic test facilities, such as shock tunnels. The long test times and short turn-around times here are important, enabling relatively rapid development of non-intrusive optical diagnostics which would be difficult to achieve in larger, short-pulse facilities. A detailed description of the system is given in Ref. [1].

The goals of this program are multi-fold. We wish to

1. Obtain experimental data on molecular energy transfer mechanisms and rates to enable predictive modeling of high-speed non-equilibrium flow fields.
2. Develop instrumentation to measure temperature, vibrational populations, and species concentrations in air flows. The instrumentation includes high frame rate nitric oxide planar laser induced fluorescence (NO PLIF), high frame rate nitric dioxide molecular tagging velocimetry (NO_2 MTV), picosecond coherent anti-Stokes Raman spectroscopy (ps CARS), two-photon absorption laser induced fluorescence spectroscopy (TALIF), and Thomson scattering.
3. Demonstrate use of such instrumentation to obtain data in short duration hypersonic flow facilities, i.e., in large scale shock tunnels and blow-down wind tunnels.
4. Develop methods of actively influencing flow field energy storage, energy transfer, and aerodynamic control.

Considerable progress towards achieving these goals has been made. We review some of the more significant developments here.

2.1. *Wind tunnel configuration*

Fig. 1 shows schematic layouts of this wind tunnel. The top drawing is the side view of the system; the bottom drawing is an enlarged top view of the tunnel plenum only. The tunnel walls are made of heavy acrylic plastic. The low gas kinetic temperatures in the flow permit this, despite the very high energy loading of some of the internal molecular modes. Gas flow is from left to right in the figure. Upstream, dry air or nitrogen gas is injected into a flowing plenum section. Gases are supplied at plenum pressures of $P_0 = 0.5–1.0$ atm. Steady-state non-equilibrium supersonic flow in the wind tunnel is produced by sustaining a high-pressure electric discharge in the plenum. Here, two pairs of electrodes are arranged to provide orthogonal current flow paths. These electrodes create two fully overlapping discharges in a rectangular cross section channel 1 cm in height and 4 cm wide (see Fig. 1). The first is a transverse, nanosecond pulse discharge sustained between two plane dielectric barrier electrodes flush mounted in the top and bottom walls of the discharge section, and operated at a high pulse repetition rate of $\nu = 100$ Hz. The second is a transverse dc discharge sustained between two copper plate electrodes 4 cm long with a height of 1 cm, mounted in the side walls of the discharge section.

The main purpose of the two overlapping discharges is to generate stable non-equilibrium plasmas at high plenum pressures and discharge energy loadings. The repetitive nanosecond pulse discharge is operated using a high peak voltage (up to 30 kV), short pulse duration (5 ns) pulse generator. Volume ionization in the discharge section is generated during each high-voltage pulse, after which the voltage is turned off before ionization/heating instability has time to develop. Between the ionizing pulses, energy is coupled to the flow by the dc discharge, sustained in the ionized flow created by the pulser. The dc voltage is deliberately kept low below breakdown threshold, typically below 4–5 kV, to preclude development of a self-sustained (i.e., independent of pulsed ionization) dc discharge in the high

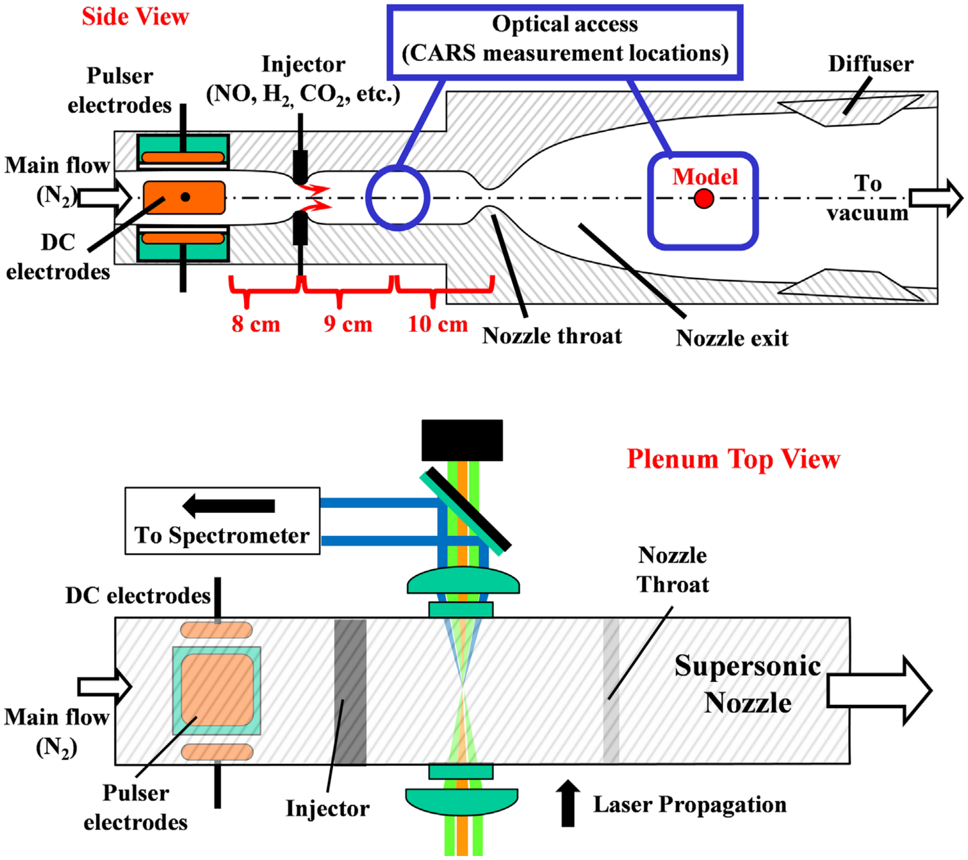

Fig. 1. Schematic of the Mach 5 nonequilibrium plasma wind tunnel.