5. FLOWING AIR PLASMAS: KINETICS, RELAXATION RATES, AND FLOW DYNAMICS

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Abstract. In this work we model an idealized supersonic-flow, pulsed-excitation experiment based on actual recent studies. We use a two-term Boltzmann equation solver with well-tested electron impact cross section sets for O\textsubscript{2} and N\textsubscript{2} to estimate the energy deposition rates into the many internal states of oxygen and nitrogen. We argue, based on Navier-Stokes flow calculations, that the amount of stored energy and the known relaxation phenomena associated with these plasmas can lead to energy deposition into the T-R degrees of freedom at a rate fast enough to perturb the flow and alter the drag.

Introduction

There has been considerable recent interest in flow phenomena in weakly ionized plasmas [1]. Changes in drag coefficient, shock wave standoff distance and changes in shock wave propagation are among the effects observed in such plasmas compared to flows in unionized air. Although the fractional ionization is low in these reduced pressure (tens of torr) air plasmas, the composition is complex. The air is far from thermodynamic equilibrium at the translational-rotational (T-R) temperature. Vibrational and electronic excitation and fractional dissociation occur as a result of electron impact, and subsequent relaxation and energy transfer must be considered. A key issue is the degree of detail to which these systems can be described, and how much detail is actually required to reach a useful understanding of their flow dynamics.

Experiment Modeled

- A pulsed microwave discharge excites a supersonic airflow

\[ M_c = 1.3, \ p_c = 60 \text{ torr}, \ T_c = 200 \text{K}, \]
\[ \tau_p = 2 \mu \text{s}, \]

(Operating parameters are taken from reference [2])

- The air flows over a 1.6 cm diameter sphere placed 1 cm downstream of the discharge region.

The setup is shown schematically

- Changes in drag force (~ 5%) and shock structure are observed during pulse

(These data are taken from reference [3])

- Energy absorbed by gas (about 30% of incident microwave pulse)

\[ E_g \approx 0.25 \text{ J/(cm}^3 \text{ atm)}, \quad V_{pulsed}/p = 40 \text{V/(cm torr)} \]

- Measured temperatures after pulse

\[ T_{gas} < 250 \text{K}, \quad T_{vib}(N_2) \approx 1500 \text{K} \]

Discharge Calculations

- Utilize BOLSIG - a two-term Boltzmann equation solver coupled with a set of excitation cross sections for N\textsubscript{2} and O\textsubscript{2} [4]

- Specify the experimental conditions as stated above and solve for "initial" excited state distribution (Fig.1 shows the relative energy distribution in the various states). This approach is satisfactory for short discharge pulses and small fractional excitation and ionization.
Obtain state population distributions \( \sim 5 \mu s \) after the pulse utilizing rate constants available for all the important excited states.

![Figure 1: Excited-state energy distribution (Air, 40V/cm torr)](image1)

### Results of Discharge Calculations

- After 5\( \mu s \), the only important excited species are \( N_2 \) \( (X,v=1-8) \), and O-atoms. All electronically excited species are collisionally quenched except for small amounts of \( O_2(\Delta) \) and \( O_2(\Sigma) \). The number densities are shown in Fig.2.

![Figure 2: State Population After 5\( \mu s \) (\( \Delta T=30K \))](image2)

- High-lying electronic states of \( N_2 \) are rapidly quenched by \( O_2 \) and/or \( N_2 \) to \( N_2(\Lambda \Sigma) \), releasing \( O \)-atoms and/or energy [5].

- \( N_2(\Lambda) \) is very rapidly quenched to \( N_2(X) \) by \( O_2 \), yielding ground-state oxygen atoms. Quenching by \( N_2(X) \) is several orders of magnitude slower[6].

\[
N_2(\Lambda) + O_2 \rightarrow N_2(X) + 2O + \text{energy} \\
k \leq 2 \times 10^{-12} \text{ cm}^3/\text{s}
\]

- \( O_2(B^3\Sigma) \) produced around 8.4eV above the ground state immediately dissociates to \( O(1D) \) and ground-state \( O(3P) \), plus energy.

Then [7],
\[
O(1D) + N_2 \text{ (or } O_2) \rightarrow O(3P) + N_2 \text{ (or } O_2) + \text{energy} \\
k \geq 5 \times 10^{-11} \text{ cm}^3/\text{s}
\]

### Summary of discharge calculations

After 5\( \mu s \) or so, the pulse-excited flow volume can be taken to be \( N_2, O_2, N_2(\nu), \) and \( O \). In particular, the small amounts of excited oxygen can be neglected. We assume that the energy released in the collisional quenching of electronically excited nitrogen and oxygen (the energy in excess of that used to produce ground-state atoms) rapidly appears as heat. This excess energy is about 20\% of the total pulse input and raises \( T \) in the excited volume by \( \sim 30K \).

### Flow calculations

These calculations are performed utilizing the cylindrical symmetry of the flow, and solving the species mass conservation equations and the momentum conservation equations (Navier-Stokes equations), and energy conservation equations. Calculations were done with and without \( N_2(\nu) \) vibrational relaxation by \( O \)-atoms. The code is described in detail in ref.[8].

The effect of vibrational relaxation on \( N_2 \) by \( O \) is negligible for the short flow times appropriate for this experiment - times of the order of 0.1ms. About half the absorbed discharge energy is in \( N_2 \), and this energy could cause an additional T-rise of about 75K if released. However, the \( O \)-atom concentration is about \( 1.8 \times 10^{16} \), and the relaxation rate is about \( 3.5(\nu) \times 10^{-15} \text{cm}^3/\text{s} \) [9]. The first-order decay time therefore ranges from 2-15 ms, and less than 1\% of the vibrational energy is available as heat.

However, the effect of the heated volume of air itself is not negligible. Figure 3 shows the behavior of the drag during the 150\( \mu s \) interval that the model interacts with the flow. The three curves correspond to three different assumed volumes with
the same total heat addition, so that the temperature increase varies inversely with volume. Although the oscillations are different, the average change integrated over 200ms corresponds to a drag decrease of about 4%.

Fig.3. Drag coefficient for 1.6cm sphere (for $p=60$torr, $T=200K$, $M=1.3$)

Conclusions

It is apparent that interpreting and modeling the data from a pulsed discharge flow experiment of this type requires care. The rapid initial heat addition is sufficient to produce measurable transient drag changes. The role of vibrational relaxation will depend on the scale of the experiment. If the length scale, and therefore the flow times, were 10 times longer, vibrational relaxation would play a role. Similarly, the results will vary nonlinearly with increasing excitation and dissociation. All of these effects result from changing the enthalpy of the gas, and the degree to which the excited internal degrees of freedom relax during the characteristic interaction time of the flow with the model.

References