Detailed Investigation of Nonequilibrium Effects on Aero-Optics in Hypersonic Flows

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1 Statement of problem

The United States Air Force identified hypersonic technologies as being a primary focus of future development in their *2010 Technology Horizons* [1] as well as affirmed the importance of hypersonic technology to national security [2]. One primary intention of these hypersonic platforms is for responsive Intelligence, Surveillance, and Reconnaissance. It is common for these types of missions to employ Radio Frequency and Electro-Optical/Infrared sensors to collect information. However, these optical signals are very sensitive to the flow field it travels through, especially the density [3]. If an optical signal were to travel through a hypersonic flow field, a detailed understanding of the flow field properties would be required to accurately determine optical distortions and sensor performance. The hypersonic flow field is very complex, which includes nonequilibrium, reactive flows (i.e. chemistry), energy transfer between molecular energy modes, turbulence, boundary layers, and shocks, all of which could effect optical signals either directly or indirectly. This proposed research will investigate the effect nonequilibrium flows, characteristic of hypersonic flight, have on flow-induced distortions. This includes:

1. Utilizing state-of-the-art thermochemical modeling and applying it to the application of aero-optics.

2. Implementing different rates for the thermochemical modeling to identify the sensitivity of the results to the differing rates of the nonequilibrium community.

3. Identifying and enveloping conditions of interest where nonequilibrium effects are important in hypersonic flows to the application of aero-optics.

2 Background and relevance to previous work

Numerous aspects of any flow field can be a potential cause of signal distortion and aberration. Turbulence is a common cause of optical signal distortion. This has been widely studied in the atmosphere [4, 5] and, most recently, near the optical window of flight vehicles [3]. However, most of the aero-optical research to date has been for low speed applications [3]. These optical distortions are quantified using optical path length (OPL) and optical path difference (OPD). These distortions can be quantified using the Gladstone-Dale relation that was derived for eqiulibrium, low-temperature gas in the 19th century [6]. A recent study investigated limited high speed cases (i.e. hypersonic flow) but it was for flow over a flat plate and primarily investigated the effect of hypersonic turbulence on the optical sensors [7]. This work will investigate stronger shocks (e.g. normal shocks) with more of a focus on the effect of nonequilibrium, high-temperature flows on the optical distortions.

Hypersonic flight is characterized by complex flow phenomena including thin shock layers, an entropy layer, viscous interactions, and low-density, high temperature flows. The high-temperature flow results in real-gas effects becoming important, and the flow being in state of thermal nonequilibrium and chemically reactive (i.e. dissociation and ionization of the gas). Due to the complexity of the flow there has been limited research on the effect of high-temperature effects on the optical distortions. Recently, there has been experimental studies on the effect of nonequilibrium on aero-optics [8, 9] and this work proposes to complement this work by creating a better understanding of the basic theory of aero-optics in a hypersonic flow and building the modeling and simulation capabilities to study it extensively.

3 General methodology and procedure to be followed

The hypersonic flight regime involves an extremely high level of energy so even a small error in the modeling of the energy processes can result in drastic changes in the vehicle design, which motivates modeling the physics involved at a high-fidelity. Behind a strong shock wave characteristic of hypersonic flight, the gas reaches a significantly high temperature which results in thermochemical nonequilbrium as the gas is excited and ionized by collisional processes. This nonequilibrium causes the the populations of quantum states to be no longer governed by a Boltzmann distribution but rather by collisional and radiative processes.

Two different approaches for modeling the nonequilibrium physics of the post shock flow will be utilized, the 2T and the STS models [10]. The two-temperature (2T) approach is the most commonly used approach for hypersonic vehicle analysis. Nonequilibrium in the energy transfer is described by separating the trans-rotational energy and the vibrational-electronic-electron energy. The 2T model employs a geometrically averaged temperature of the translational and vibrational temperature (e.g. $T = \sqrt{T_t T_v}$) in order to model nonequilibrium effects. The state-to-state (STS) approach is a higher fidelity model for describing the nonequilibrium energy transfer. The STS model is computationally expensive since it directly simulates the population of each vibrational state. These populations are governed by the system of master equations that employ state-specific rates obtained by quasiclassical trajectory (QCT) simulations or more general models such as the forced harmonic oscillator (FHO) model [11]. This approach allows for multi-quantum transitions and non-Boltzmann distributions to be captured [12, 13]. This work proposes to utilize 2T and STS modeling to investigate the effect of nonequilibrium on the optical distortions.

4 Explanation of new or unusual techniques

The primary investigator has developed or co-developed state of the art modeling techniques for nonequilibrium flows that range in fidelity, dimension, and computational cost. This includes a one dimensional code (i.e. shock tube) that can model 2T, STS, or even 4T-STS [14]. There is also significant nonequilibrium modeling development ongoing at AFRL/RQ Wright Patterson [15], which allows for natural collaboration in this area. But the STS codes are only as accurate as the rates (bound-bound and bound-free) that are implemented. There are currently different rates from different research groups, which derive these rates using different approaches and potential energy surfaces [16, 17, 18]. AFRL/RQ Wright Patterson researchers are also generating a database of these rates for conditions of interest. However, there is uncertainty to which set of rates is most appropriate and differences to experimental data still exist [19]. This work proposing to implement these rates in the nonequilibrium modeling techniques to accurately model the hypersonic flow field. If the hypersonic flow field is modeled correctly, then the effect of nonequilibrium on aero-optics can be quantified for conditions of interest.

5 Expected results and their significance and application

The expected results of this work is a quantification of the effects of thermal and chemical nonequilibrium on hypersonic aero-optics. This includes enveloping the conditions of interest where nonequilibrium can effect the aero-optical properties of the flow. A secondary result of this work will be a detailed study of different STS rates and their induced sensitivity to the flow field properties. This proposed work is novel and significant work because there has been limited research in nonequilibrium/hypersonic aero-optics and a better understanding of it's behavior directly correlates to national security as motivated in Section 1.

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6 Graduate Student Application

The application for doctoral student Martin Liza is attached.