THE OHIO STATE UNIVERSITY
COLLEGE OF ENGINEERING

# Physical Gas Dynamics

## MECHENG 8504

**Credit Hours:**
3.00 - 3.00

**Course Levels:**
Graduate (5000-8000 level)

**Course Components:**
Lecture
Independent Study

**Course Description:**
Physics of nonequilibrium, reacting, ionized gas flows. Analysis of molecular energy transfer processes, chemical reactions, and ionization processes. Applications for hypersonic reentry flows, high-speed flow control, and molecular lasers.

**Prerequisites and Co-requisites:**
Prereq: 8503 (803) or equiv, or permission of instructor.

**Course Goals / Objectives:**
- Introduce students to physics of nonequilibrium, reacting, ionized gas flows. Demonstrate key importance of "real gas" effects for high-enthalpy flows
- Cover necessary background in statistical thermodynamics and kinetic theory
- Understand basic concepts of molecular energy transfer processes, chemical reactions, and ionization processes, and their coupling with the flow, through analysis of open-ended problems
- Provide an overview of current and emerging engineering applications, such as hypersonic reentry flows, high-speed flow control, and molecular lasers

**Course Topics:**

- Overview of “real gas” effects and kinetic processes in high-enthalpy flows. Internal structure of molecules and atoms: wavefunctions, quantum states, energy levels. Examples: particle in a box, hydrogen atom, harmonic oscillator, rigid rotor.
- Maxwell-Boltzmann (M-B) statistics. Thermodynamic probability and entropy. Derivation of Boltzmann distribution using Lagrange multipliers. Partition function and its relationship to thermodynamic functions. Equation of state of a perfect gas.
- Thermodynamic functions and energy distributions for perfect gas, linear harmonic oscillator, and rigid rotor. Partition functions and energy levels for systems with multiple degrees of freedom. Specific heat of a diatomic molecule vs. temperature.
- Standard formation enthalpy and heat of reaction. Chemical potential and thermodynamics of gas mixtures. Chemical equilibrium. Mass action law. Change of Gibbs free energy of reaction. Equilibrium constant and its relation to heat of reaction.
- Equilibrium chemical composition of gas mixtures. Examples: (a) dissociation of diatomic molecules, (b) ionization of atoms - Saha equilibrium. Effect of dissociation and ionization on specific heat. “Frozen” and “equilibrium” specific heat.
- Effects of heat of reaction and change of entropy of reaction on equilibrium composition. Calculation of equilibrium composition in multi-component systems. High-temperature equilibrium air.
- Overview of kinetic theory. Interaction potentials, collision trajectories, impact parameter, cross sections, rate coefficients, collision frequency, mean free path. Brief overview of M-B distribution averaging.
- Detailed balance. Reaction kinetic equation. Relation between forward and reverse rate coefficients and the equilibrium constant. Quasiclassical theory of bimolecular chemical reaction rate coefficients.
- Quasiclassical theory of bimolecular chemical reaction rate coefficients (continued). Unimolecular reaction rates.
- Semiclassical theory of vibration-translation (V-T) relaxation in collinear collisions.
- Vibrational energy relaxation equation and relaxation time. Vibrational relaxation behind the shock and in nozzle flows: qualitative description. Effect of molecular anharmonicity on V-T relaxation rates.
- Close coupling of multiple vibrational states during vibrational relaxation. Effect of three-dimensionality of collisions on relaxation rates. Forced Harmonic Oscillator (FHO) model.
- Vibration-vibration (V-V) energy exchange. Semiclassical theory of V-V relaxation.
- Treanor distribution. Vibrational relaxation of anharmonic oscillators and V-V pumping.
- Master equation modeling. V-V pumped distributions functions in electric discharges and optically pumped gases. Vibrationally stimulated chemical reactions, ionization, and vibration-to-electronic (V-E) energy transfer.
- Coupled vibrational relaxation and dissociation. Treanor-Marrone and Macheret-Rich dissociation models.
- Equations of a quasi-1-D, compressible, vibrationally relaxing, chemically reacting flows. Kinetics of nonequilibrium nozzle flows.
- Kinetics of vibrational relaxation, chemical reactions, ionization, and nonequilibrium radiation behind strong shock waves. Effect of relaxation on shock stand-off distance.
- High-speed flows with energy addition. Energy addition hypersonic wind tunnel: feasibility and technical issues.
- Brief overview of plasmas. Electrons and ions. Quasineutrality and Debye length. Thermal and non-thermal ionization processes (electron impact and photo-ionization). Recombination and electron attachment. Equilibrium and nonequilibrium plasmas.
- Basics structure of DC glow discharge, RF/microwave discharge, and dielectric barrier (DBD) discharges. Sheath (space charge) regions.
- Equations of ionized compressible flows in the presence of electric and magnetic fields. Electrohydrodynamic (EHD) flow control. Surface dielectric barrier discharge (DBD) plasma actuators and

their use for airfoil flow control.
- Magnetohydrodynamic (MHD) flow acceleration, power generation, and flow control. Applications for reentry flows and hypersonic inlet flows.
- Shock wave generation and high-speed flow control using rapid localized energy release. Localized arc filament plasma actuators (LAFPA), surface DBD plasma actuators powered by nanosecond duration voltage pulses and their use for flow control.
- Spontaneous emission and collisional quenching of excited states. Absorption and stimulated emission. Population inversion and laser gain.
- CO2 laser. Gas dynamic lasers: use of rapid supersonic expansion to achieve population inversion. Partial inversion, mechanism of operation, and gain of a CO laser.
- Gas dynamics lasers (continued). Mechanism of operation and gain of a chemical oxygen-iodine laser (COIL). Electric discharge pumped COIL.

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**Designation:**
Elective