Plasma Dynamics for Aerospace Engineering

This valuable resource summarizes the past fifty years' basic research accomplishments in plasma dynamics for aerospace engineering, presenting these results in a comprehensive volume that will be an asset to any professional in the field. It offers a comprehensive review of the foundation of plasma dynamics while integrating the most recently developed modelling and simulation techniques with the theoretic physics, including the state-of-the-art numerical algorithms. Several first-ever demonstrations for innovations and incisive explanations for previously unexplained observations are included. All the necessary formulations for technical evaluation to engineering applications are derived from the first principle by statistic and quantum mechanics, and led to physics-based computational simulations for practical applications. The computer-aided procedures directly engage the reader to duplicate findings that are nearly impossible by using ground-based experimental facilities. *Plasma Dynamics for Aerospace Engineering* will allow readers to reach an incisive understanding of plasma physics.

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Preface

Infusing plasma physics into engineering applications was initiated as early as the 1940s. At the beginning it was tentatively used to investigate nuclear fusion and fission problems, and then it was applied to astrophysics and geophysics to better understand the earth's magnetic field and Van Allen belts, as well as solar wind phenomena. In the later 1950s scientists and engineers pioneered space exploration; plasma science was used to answer the formidable engineering challenges presented by reentry thermal protection and telecommunication blackout issues. At the same time, the ion thruster was initialized for satellites' station keeping and interplanetary flights. However, the plasma dynamics research for engineering applications has experienced a rise and ebb for the past fifty years. Scientists and engineers rejuvenated plasma research interest in the early 1990s by advocating the concept of magnetohydrodynamic-bypass scramjet engines. Since then an extremely wide range of plasma applications was generated on remote energy deposition for flight vehicle drag reduction, flow control by plasma actuator, radiation-driven hypersonic wind tunnels, sonic boom mediation, and enhanced ignition and combustion stability. The plasma applications in traditional sterilization and pasteurization now have also been extended to wound healing and tissue regeneration.

Today plasma dynamic research for engineering applications has been sustained worldwide; any sizable technical symposia will have many sessions on this vigorous research arena. More than a thousand articles have been presented and published at international conferences and in professional journals. However, nearly all plasma only exists in a high-enthalpy, nonequilibrium, thermodynamic state that is rarely supportable by ground-based experimental facilities. Modeling and simulation capability for plasma dynamic research becomes mandatory for a scientific discipline that must be studied in extremely demanding environments. Scholars have published excellent books and superb treatises on classic plasma dynamics, but very few neither bridge the gap between theoretical physics and computational simulations, nor summarize the most recent progress. Some of the current research efforts are still conducted in isolation to reveal the need for guidance in a productive research direction based on accumulated knowledge. More important, it is crucial to share and to disseminate basic knowledge for mutual support in science and engineering. The present manuscript intends to carry out that humble service by sharing research accomplishments and converting the research results into knowledge for future advancement. For this reason, this text is prepared as a professional reference for researchers and, we hope, as a textbook for advanced engineering graduate study in plasma dynamics.

For these purposes, a variety of multi-physics models that couple quantum physical-chemical and radiative processes with gas dynamics is assembled. In this aspect, the engineering approaches based on continuum mechanics for describing high enthalpy ionized gas include thermodynamics, statistical quantum physics, nonequilibrium chemical kinetics, and transport property via gas kinetic theory with computational fluid dynamics techniques. All these approaches are based on the Born-Oppenheimer approximation involving a wide range of the resonant energy exchange between quantum states. For flow control using electron impact ionization, the recent innovation is presented in detail by combining the classic drift-diffusion theory with inelastic collision quantum-chemistry models for ionized species generation and depletion through quantum transitions. The rigorous boundary conditions at the interfaces across electrodes and plasma are derived from the Maxwell equations, which explain fully the self-limiting feature of the direct barrier charge that prevents transition from discharge to spark. In view of the diversity of all methodologies, the uncertainty in our knowledge of chemical kinetic modeling inviolably leads to many unresolved issues. At the same time, the reliable computational methods still have not yet been completely resolved, despite the significant progress researchers and scientists have made in recent decades.

For radiative energy transfer, a systematic presentation from the classic multi-flux methods that build on the Milne-Eddington approximation is highlighted. For the important interaction between radiation and gas dynamics, the direct computational simulation that interweaves the radiation rate equation with gas dynamics and quantum optic physics is included. The directly usable methods for volumetric emission to analyze optical thin and dense gas, as well as the influence by the fine structure of atomic spectral line to radiation transfer utilizing ray-tracing and Monte Carlo techniques, are included as a state-of-the-art assessment.

This manuscript is organized in ten chapters; the first three chapters evolve around the basic electromagnetic phenomena and fundamental laws of plasma dynamics and electromagnetics. The linking of intrinsic characteristics of the Debye length and plasma frequency to the electrostatic force and the prolate cycloid charged particle motions in electromagnetic fields will be illustrated. The drastically altered electrical conductive property from a scalar to a tensor in an electromagnetic field is also derived. The unique and peculiar behavior of plasma under the influence of an external applied magnetic field that leads to the Hall current, magnetic mirror, and plasma confinement will also be highlighted. At this connection, a discussion of plasma instability is offered to illustrate the self-constricted pinch effect by the interaction of the static pressure gradient and the magnetic force. In Chapter 3, the Maxwell equations and boundary conditions for plasma are articulated and emphasized for analytic studies and computational simulations. Furthermore, the different hydro-electromagnetic wave speeds are shown by eigenvalue analysis for the system of hyperbolic partial differential equations. At the same time, the characteristic formulation is instituted to alleviate the inherent limitation of imposing far-field boundary conditions for a boundless initial value and boundary condition problem.

The fundamental plasma formulation for analytic and computational simulations is detailed in Chapter 4 from the first principle, and the best current practices are included. A detailed and progressive evolution from the Boltzmann-Maxwell, Fokker-Plank, and Vlasov equations to the most frequently adopted multi-temperature and multi-fluid plasma models will be systematically introduced. The important transport property of ionized gas will be described from the collision kinetics through the collision integrals with a screened Coulomb potential and verified by experimental observations. The inter-nuclear interaction by inelastic collision kinetics is utilized to develop the drift-diffusion theory as a viable plasma modeling for the electron impact ionization.

The classic formulation of magnetohydrodynamics (MHD), which is built on the generalized Ohm's law, is presented next to link the physical observations and approximated numerical simulations. One of the underlying assumptions is that neglecting the effect of displacement electric current actually limits the simulated plasma phenomena beneath the microwave frequency. Equally important, plasma is treated as a multicomponent fluid medium; the electric conductivity is simplified to become a scalar constant. Therefore, the formulation when applying for practical engineering applications is restricted to the low magnetic Reynolds number environment. Chapter 5 also points out the elegance of analytical clarity, and the limitations of computational simulations using magnetohydrodynamic equations and defining the valid scope for the classic approximations.

In the next two chapters, the ionizations of gas and the plasma generation process are articulated. The collision transfer and the energy states are quantum restricted, but the individual mechanism still can be distinctively described. Chapter 6 delineates the basic mechanisms of ionization, which include elastic and inelastic collisions, electronic impact, radiative interaction, charge exchange, dissociation recombination, dielectric recombination, and electron attachment. The interconnection between the microscopic particle dynamics and the macroscopic properties of the ionized gas is first illustrated by the statistic thermodynamics in equilibrium condition, then by nonequilibrium collisional kinetic theory, and it is finally treated by the general principle of computational quantum chemistry. The plasma generation processes for engineering applications are presented in Chapter 7, in which the plasma generations from electron impact, shock tube, arc plasmatron, electromagnetic induction, microwave excitation, to ionization by radiation are included with descriptions of existent capabilities.

In Chapter 8, all practical plasma diagnostic techniques are presented with supporting experimental observations and accuracy assessments. The plasma diagnostics techniques are systematically presented from the classic Langmuir probe to the nonintrusive approaches such as spectrometry and the microwave attenuation principle. The concept of the retarding potential analyzer is included for detecting the ion energy distribution in ion thrusters at high temperature conditions. Based on these scientific disciplines, the necessary quantification and qualification of plasma parameters for applications can be determined.

Chapter 9 addresses the very important and the most complex issues of plasma emission, absorption, and scattering spectroscopic phenomenon by radiation. In theory, the fundamental approach must be built on the perturbation theory of quantum mechanics and a thorough understanding of atomic and molecular spectral structures and collision kinetics. Therefore, the discussion starts from the Boltzmann equation for photon dynamics, and then leads to the phenomenological approach and finally to the general practices of solving radiative energy transfer equations for engineering applications. The traditional methods of multi-flux approach – the half-moment, spherical harmonics, and method of discrete ordinate – are included. The detailed and directly usable methods based on computational gas dynamic radiation by ray-tracing and Monte Carlo methods are carefully assessed for their physical fidelity. Some of the cornerstone validating computational investigations and computational results are also presented and discussed.

Chapter 10 summarizes the most viable applications of plasma dynamics to engineering; the current progress and unique features in electrostatic and Hall ion thrusters are incorporated and evaluated for their capability of and potential for interplanetary explorations. Only a brief, but critically important summary of radiation heat transfer for reentry thermal protection is presented. The plasma actuators for flow control either by Joule heating or by electrostatic and Lorentz forces are highlighted for best practices. Using plasma for enhancing ignition and maintaining combustion stability, together with the remote energy deposition by microwave, are brought out as the current innovation in plasma applications. Other possible applications, such as the magnetohydrodynamics scramjet bypass and pulsed plasma thrusters, are also included.

Finally, last but not least, we would like to express our sincere appreciation to our colleagues in the scientific research community and our gratitude for the lifetime benefit of learning from each other.