Macroscopic Transport Equations For Rarefied Gas Flows Approximation Methods In Kinetic Theory 1st E

Multiscale Thermo-Dynamics
Entropy and Non-Equilibrium Statistical Mechanics
Microscale Flow and Heat Transfer
Modeling Evaporation in the Rarefied Gas Regime by Using Macroscopic Transport Equations
Non-Equilibrium Reacting Gas Flows
From Kinetic Models to Hydrodynamics
Mesoscopic Theories of Heat Transport in Nanosystems
The Mathematical Theory of Dilute Gases
Moment Method in Rarefied Gas Dynamics
An Introduction to Fluid Mechanics and Transport Phenomena
Kinetic Theory of Gases in Shear Flows
The Boltzmann Equation and Its Applications
Rarefied Gas Dynamics

Macroscopic Description of Rarefied Gas Flows in the Transition Regime
Kinetic Theory and Fluid Dynamics
Proceedings, "WASCOM 2007"
Applications of Chaos and Nonlinear Dynamics in Science and Engineering - Vol. 4
Extended Thermodynamics
Direct Methods for Solving the Boltzmann Equation and Study of Nonequilibrium Flows
Model Reduction and Coarse-Graining Approaches for Multiscale Phenomena
Gas Transport in Porous Media
Charge Transport in Low Dimensional Semiconductor Structures
A Modern Course in Transport Phenomena
Macroscopic Transport Equations for Rarefied Gas Flows
The Relativistic Boltzmann Equation: Theory and Applications
Interacting Multiagent Systems
A Modern Course in Transport Phenomena
Classical and Relativistic Rational Extended Thermodynamics of Gases
Atoms, Mechanics, and Probability
Granular Gaseous Flows
Parallel Computational Fluid Dynamics
Lecture Notes on the Discretization of the Boltzmann Equation
Macroscopic Description of Rarefied Gas Flows in the Transition Regime
Solving Problems in Thermal Engineering
Nonequilibrium Gas Dynamics and Molecular

Simulation
Rational Extended Thermodynamics beyond the Monatomic Gas
Transport Theory
Computational Science – ICCS 2020
Rarefied Gas Dynamics

JAXSON BANKS

Multiscale Thermo-Dynamics Cambridge University Press
This advanced text presents a unique approach to studying transport phenomena. Bringing together concepts from both chemical engineering and physics, it makes extensive use of nonequilibrium thermodynamics, discusses kinetic theory, and sets out the tools needed to describe the physics of interfaces and boundaries. More traditional topics such as diffusive and convective transport of momentum, energy and mass are also covered. This is an ideal text for advanced courses in transport phenomena, and for researchers looking to expand their knowledge of the subject. The book also includes: • Novel applications such as complex fluids, transport at interfaces and biological systems, • Approximately 250 exercises

with solutions (included separately) designed to enhance understanding and reinforce key concepts,
• End-of-chapter summaries.

Entropy and Non-Equilibrium Statistical Mechanics

Springer

One common feature of new emerging technologies is the fusion of the very small (nano) scale and the large scale engineering. The classical environment provided by single scale theories, as for instance by the classical hydrodynamics, is not anymore satisfactory. The main challenge is to keep the important details while still be able to keep the overall picture and simplicity. It is the thermodynamics that addresses this challenge. Our main reason for writing this book is to explain such general viewpoint of thermodynamics and to illustrate it on a very wide range of examples. Contents Levels of description Hamiltonian mechanics Irreversible evolution Reversible and irreversible evolution Multicomponent systems Contact geometry Appendix: Mathematical aspects

Microscale Flow and Heat Transfer

Springer Science & Business Media

From Kinetic Models to Hydrodynamics serves as an introduction to the asymptotic methods necessary to obtain hydrodynamic equations from a fundamental description using kinetic theory models and the Boltzmann equation. The work is a survey of an active research area, which aims to bridge time and length scales from the particle-like description inherent in Boltzmann equation theory to a fully established "continuum" approach typical of macroscopic laws of physics.The author sheds light on a new method—using invariant manifolds—which addresses a functional equation for the nonequilibrium single-particle distribution function. This method allows one to find exact and thermodynamically consistent expressions for: hydrodynamic modes; transport coefficient expressions for hydrodynamic modes; and transport coefficients of a fluid beyond the traditional hydrodynamic limit. The invariant manifold method paves the way to establish a needed bridge between Boltzmann equation theory and a particle-based theory of hydrodynamics. Finally, the author explores the ambitious and longstanding task of obtaining hydrodynamic constitutive equations from their kinetic counterparts. The work is intended for specialists in kinetic theory—or more generally statistical mechanics—and will provide a bridge between a physical and mathematical approach to solve real-world problems.

Modeling Evaporation in the Rarefied Gas Regime by Using Macroscopic Transport Equations Springer Science & Business Media

This book is concerned with the methods of solving the nonlinear Boltz mann equation and of investigating its possibilities for describing some aerodynamic and physical problems. This monograph is a sequel to the book 'Numerical direct solutions of the kinetic Boltzmann equation' (in Russian) which was written with F. G. Tcheremissine and published by the Computing Center of the Russian Academy of Sciences some years ago. The main purposes of these two books are almost similar, namely, the study of nonequilibrium gas flows on the basis of direct integration of the kinetic equations. Nevertheless, there are some new aspects in the way this topic is treated in the present monograph. In particular, attention is paid to the advantages of the Boltzmann equation as a tool for considering nonequi librium, nonlinear processes. New fields of application of the Boltzmann equation are also described. Solutions of some problems are obtained with higher accuracy. Numerical procedures, such as parallel computing, are in vestigated for the first time. The structure and the contents of the present book have some com mon features with the monograph mentioned above, although there are new issues concerning the mathematical apparatus developed so that the Boltzmann equation can be applied for new physical problems. Because of this some chapters have been rewritten and checked again and some new chapters have been added. Non-Equilibrium Reacting Gas Flows Springer Science & Business Media This volume is the fifth in a series of proceedings which started in 1999. The contributions include the latest results on the theory of wave propagation, extended thermodynamics, and the stability of the solutions to partial differential equations. Sample Chapter(s). Chapter 1: Reciprocal Transformations and Integrable Hamiltonian

Hydrodynamic Type Systems (334 KB). Contents: Quantitative Estimates for the Large Time Behavior of a Reaction-Diffusion Equation with Rational Reaction Term (M Bisi et al.); Linearized Euler''s Variational Equations in Lagrangian Coordinates (G Boillat & Y J Peng); Restabilizing Forcing for a Diffusive Prey-Predator Model (B Buonomo & S Rionero); Fluid Dynamical Features of the Weak KAM Theory (F Cardin); Ricci Flow Deformation of Cosmological Initial Data Sets (M Carfora & T Buchert); Fuchsian Partial Differential Equations (Y Choquet-Bruhat); Analytic Structure of the Four-Wave Mixing Model in Photoreactive Material (R Conte & S Bugaychuk); A Note about Waves in Dissipative and Dispersive Solids (M Destrade & G Saccomandi); Exponential and Algebraic Relaxation in Kinetic Models for Wealth Distribution (B Dring et al.); Solitary Waves in Dispersive Materials (J Engelbrecht et al.); A GinzburgOCoLandau Model for the Ice-Water and Liquid-Vapor Phase Transitions (M Fabrizio); Stability Considerations for Reaction-Diffusion Systems (J N Flavin); A Mechanical Model for Liquid Nanolayers (H Gouin); A

Particle Method for a Lotka-Volterra System with Nonlinear Cross and Self-Diffusion (M Groppi & M Sammartino); Transport Properties of Chemically Reacting Gas Mixtures (G M Kremer); Navier-Stokes in Aperture Domains: Existence with Bounded Flux and Qualitative Properties (P Maremonti); On Two-Pulse Interaction in a Class of Model Elastic Materials (A Mentrelli et al.); On a Particle-Size Segregation Equation (C Mineo & M Torrisi); Problems of Stability and Waves in Biological Systems (G Mulone); Multiple Cold and Hot Second Sound Shocks in HE II (A Muracchini & L Seccia); Differential Equations and Lie Symmetries (F Oliveri et al.); Bifurcation Analysis of Equilibria in Competitive Logistic Networks with Adaptation (A Raimondi & C Tebaldi); Poiseuille Flow of a Fluid Overlying a Porous Media (B Straughan); Analysis of Heat Conduction Phenomena in a One-Dimensional Hard-Point Gas by Extended Thermodynamics (S Tanigushi et al.); On Waves in Weakly Nonlinear Poroelastic Materials Modeling Impacts of Meteorites (K Wilmanski et al.); and other papers. Readership: Researchers in mathematics, physics, chemistry and engineering."

From Kinetic Models to Hydrodynamics Springer Science & Business Media
The kinetic theory of gases as we know it dates to the paper of Boltzmann in 1872. The justification and context of this equation has been clarified over the past half century to the extent that it comprises one of the most complete examples of many-body analyses exhibiting the contraction from a microscopic to a mesoscopic description. The primary result is that the Boltzmann equation applies to dilute gases with short ranged interatomic forces, on space and time scales large compared to the corresponding atomic scales. Otherwise, there is no a priori limitation on the state of the system. This means it should be applicable even to systems driven very far from its eqUilibrium state. However, in spite of the physical simplicity of the Boltzmann equation, its mathematical complexity has masked its content except for states near eqUilibrium. While the latter are very important and the Boltzmann equation has been a resounding success in this case, the full potential of the Boltzmann equation to describe more general nonequilibrium states remains

unfulfilled. An important exception was a study by Ikenberry and Truesdell in 1956 for a gas of Maxwell molecules undergoing shear flow. They provided a formally exact solution to the moment hierarchy that is valid for arbitrarily large shear rates. It was the first example of a fundamental description of rheology far from eqUilibrium, albeit for an unrealistic system. With rare exceptions, significant progress on nonequilibrium states was made only 20-30 years later.

Mesoscopic Theories of Heat Transport in Nanosystems MDPI

Problems after each chapter

The Mathematical Theory of Dilute Gases Springer Science & Business Media

The fast-paced growth in microelectromechanical systems (MEMS), microfluidic fabrication, porous media applications, biomedical assemblies, space propulsion, and vacuum technology demands accurate and practical transport equations for rarefied gas flows. It is well-known that in rarefied situations, due to strong deviations from the continuum regime, traditional fluid models such as Navier-Stokes-Fourier (NSF) fail. The shortcoming of continuum models is rooted in nonequilibrium behavior of gas particles in miniaturized and/or low-pressure devices, where the Knudsen number (Kn) is sufficiently large. Since kinetic solutions are computationally very expensive, there has been a great desire to develop macroscopic transport equations for dilute gas flows, and as a result, several sets of extended equations are proposed for gas flow in nonequilibrium states. However, applications of many of these extended equations are limited due to their instabilities and/or the absence of suitable boundary conditions. In this work, we concentrate on regularized 13-moment (R13) equations, which are a set of macroscopic transport equations for flows in the transition regime, i.e., Kn?1. The R13 system provides a stable set of equations in Super-Burnett order, with a great potential to be a powerful CFD tool for rarefied flow simulations at moderate Knudsen numbers. The goal of this research is to implement the R13 equations for problems of practical interest in arbitrary geometries. This is done by transformation of the R13 equations and boundary conditions into general curvilinear coordinate systems. Next steps include adaptation of the transformed equations in order to solve some of the popular test cases, i.e., shear-driven, force-driven, and temperature-driven flows in both planar and curved flow passages. It is shown that inexpensive analytical solutions of the R13 equations for the considered problems are comparable to expensive numerical solutions of the Boltzmann equation. The new results present a wide range of linear and nonlinear rarefaction effects which alter the classical flow patterns both in the bulk and near boundary regions. Among these, multiple Knudsen boundary layers (mechanocaloric heat flows) and their influence on mass and energy transfer must be highlighted. Furthermore, the phenomenon of temperature dip and Knudsen paradox in Poiseuille flow; Onsager's reciprocity relation, two-way flow pattern, and thermomolecular pressure difference in simultaneous Poiseuille and transpiration flows are described theoretically. Through comparisons it is shown that for Knudsen numbers up to 0.5 the compact R13 solutions exhibit a good agreement with expensive solutions of the Boltzmann equation.

Moment Method in Rarefied Gas Dynamics

Springer Nonequilibrium statistical mechanics has a long history featuring diverse aspects. It has been a major research field in physics and will remain so in the future. Even regarding the concept of entropy, there exists a longstanding problem concerning its definition for a system in a state far from equilibrium. In this Special Issue, we offered the possibility to discuss and present up-to-date problems that were not necessarily restricted to statistical mechanics. Theoretical and experimental papers are both presented, in addition to unifying research works. As the entropy itself is the central element of nonequilibrium processes, papers discuss various formulations of the second law and its consequences. In this Special Issue, recent progress in kinetic approaches to hydrodynamics, rational extended thermodynamics, entropy in a strongly nonequilibrium stationary state, and related topics are reported as both review articles as well as original research works.

An Introduction to Fluid Mechanics

and Transport Phenomena Springer Science & Business Media Physicists firmly believe that the differential equations of nature should be hyperbolic so as to exclude action at a distance; yet the equations of irreversible thermodynamics - those of Navier-Stokes and Fourier - are parabolic. This incompatibility between the expectation of physicists and the classical laws of thermodynamics has prompted the formulation of extended thermodynamics. After describing the motifs and early evolution of this new branch of irreversible thermodynamics, the authors apply the theory to mon-atomic gases, mixtures of gases, relativistic gases, and "gases" of phonons and photons. The discussion brings into perspective the various phenomena called second sound, such as heat propagation, propagation of shear stress and concentration, and the second sound in liquid helium. The formal mathematical structure of extended thermodynamics is exposed and the theory is shown to be fully compatible with the kinetic theory of gases. The study closes with the testing of extended thermodynamics through the exploitation of its predictions for measurements of light scattering and sound propagation.

Kinetic Theory of Gases in Shear Flows

Springer Nature

It is well established that rarefied flows cannot be properly described by traditional hydrodynamics, namely the Navier-Stokes equations for gas flows, and the Fourier's law for heat transfer. Considering the significant advancement in miniaturization of electronic devices, where dimensions become comparable with the mean free path of the flow, it is well established that rarefied flows cannot be properly described by traditional hydrodynamics, namely the Navier-Stokes equations for gas flows, and the Fourier's law for heat transfer. Considering the significant advancement in miniaturization of electronic devices, where dimensions become comparable with the mean free path of the flow, the study of rarefied flows is extremely important. This dissertation includes two main parts. First, we look into the heat transport in solids when the mean free path for phonons are comparable with the length scale of the flow. A set of macroscopic moment equations for heat transport in solids are derived to extend the validity of Fourier's law beyond the hydrodynamics regime. These equations are derived such that they remain valid at room temperature, where the MEMS devices usually work. The system of moment equations for heat transport is then employed to model the thermal grating experiment, recently conducted on a silicon wafer. It turns out that at room temperature, where the experiment was conducted, phonons with high meanfree path significantly contribute to the heat transport. These low frequency phonons are not considered in the classical theory, which leads to failure of the Fourier's law in describing the thermal grating experiment. In contrast, the system of moment equations successfully predict the deviation from the classical theory in the experiment, and suggest the importance of considering both low and high frequency phonons at room temperature to capture the experimental results. In the second part of this study, we look into the gas-surface interactions for conventional gas dynamics when the gas flow is rarefied. An extension to the well-known Maxwell boundary conditions for gas-surface interactions are obtained by considering velocity dependency in the reflection kernel from the surface. This extension improves the Maxwell boundary conditions by providing an extra free parameter that can be fitted to the experimental datafor thermal transpiration effect in non-equilibrium flows. The velocity dependent Maxwell boundary conditions are derived for the Direct Simulation Monte Carlo (DSMC) method and theregularized 13-moment (R13) equations for conventional gas dynamics. Then, athermal cavity is considered to test and study the effect of these boundary conditions on the flow formation in the slip and early transition regime. It turns out that using velocity dependent boundary conditions allows us to change the size and direction of the thermal transpiration force, which leads to marked changes in the balance of transpiration forces and thermal stresses in the flow.

The Boltzmann Equation and Its Applications Cambridge University Press

Back Cover Text: This book addresses the study of the gaseous state of granular matter in the conditions of rapid flow caused by a violent and sustained excitation. In this regime, grains only touch each other during collisions and hence, kinetic theory is a very useful tool to study granular flows. The main difference with respect to ordinary or molecular fluids is that grains are macroscopic and so, their collisions are inelastic. Given the interest in the effects of collisional dissipation on granular media under rapid flow conditions, the emphasis of this book is on an idealized model (smooth inelastic hard spheres) that isolates this effect from other important properties of granular systems. In this simple model, the inelasticity of collisions is only accounted for by a (positive) constant coefficient of normal restitution. The author of this monograph uses a kinetic theory description (which can be considered as a mesoscopic description between statistical mechanics and hydrodynamics) to study granular flows from a microscopic point of view. In particular, the inelastic version of the Boltzmann and Enskog kinetic equations is the starting point of the analysis. Conventional methods such as Chapman-Enskog expansion, Grad’s moment method and/or kinetic models are generalized to dissipative systems to get the forms of the transport coefficients and hydrodynamic s. The knowledge of granular hydrodynamic s opens up the possibility of understanding interesting problems such as the spontaneous formation of density clusters and velocity vortices in freely cooling flows and/or the lack of energy equipartition in granular mixtures. Some of the topics covered in this monograph include: Navier-Stokes transport coefficients for granular gases at moderate densities Long-wavelength instability in freely cooling flows Non-Newtonian transport properties in granular shear flows Energy nonequipartiti on in freely cooling granular mixtures Diffusion in strongly sheared granular mixtures Exact solutions to the Boltzmann equation for inelastic Maxwell models *Rarefied Gas Dynamics* Springer Science & Business Media Chaos and nonlinear dynamics initially developed as a new emergent field with its foundation in physics and applied mathematics. The highly generic, interdisciplinary quality of the insights gained in the last few decades has spawned myriad applications in almost all branches of science and technology—and even well beyond. Wherever quantitative modeling and analysis of complex, nonlinear phenomena is required, chaos theory and its methods can play a key role. his fourth volume concentrates on reviewing further relevant contemporary applications of chaotic and nonlinear dynamics as they apply to the various cuttingedge branches of science and engineering. This encompasses, but is not limited to, topics such as synchronization in complex networks and chaotic circuits, time series analysis, ecological and biological patterns, stochastic control theory and vibrations in mechanical systems. Featuring contributions from active and leading research groups, this collection is ideal both as a reference and as a ‘recipe book’ full of tried and tested, successful engineering applications.

Macroscopic Description of Rarefied Gas Flows in the Transition Regime

Springer

This monograph is intended to provide a comprehensive description of the rela tion between kinetic theory and fluid dynamics for a time-independent behavior of a gas in a general domain. A gas in a steady (or time-independent) state in a general domain is considered, and its asymptotic behavior for small Knudsen numbers is studied on the basis of kinetic theory. Fluid-dynamic-type equations and their associated boundary conditions, together with their Knudsen-layer corrections, describing the asymptotic behavior of the gas for small Knudsen numbers are presented. In addition, various interesting physical phenomena derived from the asymptotic theory are explained. The background of the asymptotic studies is explained in Chapter 1, accord ing to which the fluid-dynamic-type equations that describe the behavior of a gas in the continuum limit are to be studied carefully. Their detailed studies depending on physical situations are treated in the following chapters. What is striking is that the classical gas dynamic system is incomplete to describe the behavior of a gas in the continuum limit (or in the limit that the mean free path of the gas molecules vanishes). Thanks to the asymptotic theory, problems for a slightly rarefied gas can be treated with the same ease as the corresponding classical fluid-dynamic problems. In a rarefied gas, a temperature field is di rectly related to a gas flow, and there are various interesting phenomena which cannot be found in a gas in the continuum limit.

Kinetic Theory and Fluid Dynamics

Springer Science & Business Media

Due to failure of the continuum hypothesis for higher Knudsen numbers, rarefied gases and microflows of gases are particularly difficult to model. Macroscopic transport equations compete with particle methods, such as the direct simulation Monte Carlo method (DSMC) to find accurate solutions in the rarefied gas regime. Due to growing interest in micro flow applications, such as micro fuel cells, it is important to model and understand evaporation in this flow regime. To gain a better understanding of evaporation physics, a non-steady simulation for slow evaporation in a microscopic system, based on the Navier-Stokes-Fourier equations, is conducted. The one-dimensional problem consists of a liquid and vapor layer (both pure water) with respective heights of 0.1mm and a corresponding Knudsen number of Kn=0.01, where vapor is pumped out. The simulation allows for calculation of the evaporation rate within both the transient process and in steady state. The main contribution of this work is the derivation of new evaporation boundary conditions for the R13 equations, which are macroscopic transport equations with proven applicability in the transition regime. The approach for deriving the boundary conditions is based on an entropy balance, which is integrated around the liquid-vapor interface. The new equations utilize Onsager relations, linear relations between thermodynamic fluxes and forces, with constant coefficients that need to be determined. For this, the boundary conditions are fitted to DSMC data and compared to other R13 boundary conditions from kinetic theory and Navier-Stokes-Fourier solutions for two steady-state, one-dimensional problems. Overall, the suggested fittings of the new phenomenological boundary conditions show better agreement to DSMC than the alternative kinetic theory evaporation boundary conditions for R13. Furthermore, the new evaporation boundary conditions for R13 are implemented in a code for the numerical solution of complex, two-dimensional geometries and compared to Navier-Stokes-Fourier (NSF) solutions. Different flow patterns between R13 and NSF for higher Knudsen numbers are observed which suggest continuation of this work.

Proceedings, "WASCOM 2007"
Springer Nature
This book offers, from both a theoretical and a computational perspective, an analysis of macroscopic mathematical models for description of charge transport in electronic devices, in particular in the presence of confining effects, such as in the double gate MOSFET. The models are derived from the semiclassical Boltzmann equation by means of the moment method and are closed by resorting to the maximum entropy principle. In the case of confinement, electrons are treated as waves in the confining direction by solving a one-dimensional Schrödinger equation obtaining subbands, while the longitudinal transport of subband electrons is described semiclassicall y. Limiting energy-

transport and drift-diffusion models are also obtained by using suitable scaling procedures. An entire chapter in the book is dedicated to a promising new material like graphene. The models appear to be sound and sufficiently accurate for systematic use in computer-aided design simulators for complex electron devices. The book is addressed to applied mathematicians, physicists, and electronic engineers. It is written for graduate or PhD readers but the opening chapter contains a modicum of semiconductor physics, making it self-consistent and useful also for undergraduate students.
Applications of Chaos and Nonlinear Dynamics in Science and Engineering - Vol. 4 Springer Nature
The seven-volume set LNCS 12137, 12138, 12139, 12140, 12141, 12142, and 12143 constitutes the proceedings of the 20th International Conference on Computational Science, ICCS 2020, held in Amsterdam, The Netherlands, in June 2020.* The total of 101 papers and 248 workshop papers presented in this book set were carefully reviewed and selected from 719 submissions (230 submissions to the main track and 489 submissions to the

workshops). The papers were organized in topical sections named: Part I: ICCS Main Track Part II: ICCS Main Track Part III: Advances in High-Performance Computational Earth Sciences: Applications and Frameworks; Agent-Based Simulations, Adaptive Algorithms and Solvers; Applications of Computational Methods in Artificial Intelligence and Machine Learning; Biomedical and Bioinformatics Challenges for Computer Science Part IV: Classifier Learning from Difficult Data; Complex Social Systems through the Lens of Computational Science; Computational Health; Computational Methods for Emerging Problems in (Dis-)Information Analysis Part V: Computational Optimization, Modelling and Simulation; Computational Science in IoT and Smart Systems; Computer Graphics, Image Processing and Artificial Intelligence Part VI: Data Driven Computational Sciences; Machine Learning and Data Assimilation for Dynamical Systems; Meshfree Methods in Computational Sciences; Multiscale Modelling and Simulation; Quantum Computing Workshop Part VII: Simulations of Flow and Transport:

Modeling, Algorithms and Computation; Smart Systems: Bringing Together Computer Vision, Sensor Networks and Machine Learning; Software Engineering for Computational Science; Solving Problems with Uncertainties; Teaching Computational Science; UNcErtainty QUantIficatiOn for ComputationAl modeLs *The conference was canceled due to the COVID-19 pandemic.

Extended Thermodynamics John Wiley & Sons
Aimed at both researchers and professionals who deal with this topic in their routine work, this introduction provides a coherent and rigorous access to the field including relevant methods for practical applications. No preceding knowledge of gas dynamics is assumed.

Direct Methods for Solving the Boltzmann Equation and Study of Nonequilibrium Flows
Springer
In the present monograph, we develop the kinetic theory of transport phenomena and relaxation processes in the flows of reacting gas mixtures and discuss its applications to strongly non-equilibrium conditions. The main attention is focused on the influence of non-equilibrium kinetics on gas dynamics and transport properties.

Closed systems of fluid dynamic equations are derived from the kinetic equations in different approaches. We consider the most accurate approach taking into account the state-to-state kinetics in a flow, as well as simplified multi-temperature and one-temperature models based on quasi-stationary distributions. Within these approaches, we propose the algorithms for the calculation of the transport coefficients and rate coefficients of chemical reactions and energy exchanges in non-equilibrium flows; the developed techniques are based on the fundamental kinetic theory principles. The theory is applied to the modeling of non-equilibrium flows behind strong shock waves, in the boundary layer, and in nozzles. The comparison of the results obtained within the frame of different approaches is presented, the advantages of the new state-to-state kinetic model are discussed, and the limits of validity for simplified models are established. The book can be interesting for scientists and graduate students working on physical gas dynamics, aerothermodynamics, heat and mass transfer, non-equilibrium physical-chemical kinetics, and kinetic theory of gases.

Model Reduction and Coarse-Graining Approaches for Multiscale Phenomena World Scientific

The idea for this book was conceived by the authors some time in 1988, and a first outline of the manuscript was drawn up during a summer school on mathematical physics held in Ravello in September 1988, where all three of us were present as lecturers or organizers. The project was in some sense inherited from our friend Marvin Shinbrot, who had planned a book about recent progress for the Boltzmann equation, but, due to his untimely death in 1987, never got to do it. When we drew up the first outline, we could not anticipate how long the actual writing would stretch out. Our ambitions were high: We wanted to cover the modern mathematical theory of the Boltzmann equation, with rigorous proofs, in a complete and readable volume. As the years progressed, we withdrew to some degree from this first ambition- there was just too much material, too scattered, sometimes incomplete, sometimes not rigor ous enough. However, in the writing process itself, the need for the book became ever more apparent. The last twenty years have seen an amazing number of significant results in the field, many of them published in incom plete form, sometimes in obscure places, and sometimes without technical details. We made it our objective to collect these results, classify them, and present them as best we could. The choice of topics remains, of course, subjective.

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