Journal of Fluids Engineering

Book Reviews

Fluid Dynamics and Transport of Droplets and Sprays, by W. A. Sirignano. Cambridge University Press, Cambridge, UK, 1999; 311 pages.

REVIEWED BY CHRIS F. EDWARDS[1]

[S0098-2202(00)03201-6]

Professor Sirignano and his research group have long been leaders in the development of analytical and computational approaches to treating droplet and spray flows. The monograph *Fluid Dynamics and Transport of Droplets and Sprays* is a comprehensive exposition of the state of the art in theoretical treatments of droplet and spray problems built upon that foundation. It treats the subject in a broad yet fundamental way and is particularly well suited for use by researchers who have some depth of knowledge in a particular aspect of the field but wish to obtain deeper knowledge in its other aspects. It is also suitable for use in a specialist course in analysis of droplet and spray phenomenon at the graduate level.

The text is approximately 300 pages in length and is organized such that there is a progression from simpler and more fundamental topics towards the more complex and specialized issues. Unique aspects of the text include its treatment of computational issues associated with obtaining detailed results for sprays, as well as its treatment of two current areas of spray research: particle-turbulence interaction and critical-point phenomena. Appendices are included which summarize the basic conservation equations, the hierarchy of models used to represent heat and mass transfer in spray computations, and the basis of formulation for two-continuum approaches to multiphase flows.

Chapter 1 is an overview of the important physics of droplet-gas interactions and a discussion of the scales over which these phenomena occur—effectively motivating some of the topics to be treated in later chapters. This chapter sets the stage for consideration of the spray problem by briefly noting the three current approaches to obtaining post-atomization spray conditions—empirical prescription, calculation via stability theory, and calculation via the maximum-entropy method. While the discussion of these three topics is not intended to be comprehensive, references to other suitable works are given for the interested reader.

Chapters 2 and 3 treat the simplest flow configuration—the isolated, spherical droplet vaporizing in a gaseous surrounding. In Chapter 2 discussion is confined to single-component drops; Chapter 3 extends the discussion to consider multicomponent drops including both those that are initially homogeneous (e.g., complex hydrocarbon fuels) and those that are purposefully stratified (e.g., emulsions and slurries).

In many ways Chapter 2 is the heart of the monograph. It gives a succinct yet extremely comprehensive analysis of the drop-gas transport problem from nonconvective conditions to boundary-layer gas analysis, nonvaporizing drop transport and heating to rapid, fully transient blowing, Stokes equations and matched expansions to full Navier-Stokes solutions. Besides covering the work of his own group, Sirignano provides an extensive review of the work of others and cross comparisons between results obtained using various approximations. The material in this chapter and its associated discussion will be particularly useful to those teaching droplet and spray phenomena due to both its completeness and the attention given to the limitations of the various models. Practitioners in the area of sprays will find the summaries presented in the appendix useful as well as the broad-range correlations developed by synthesizing the models into general, all-Reynolds-number expressions for Nusselt and Sherwood numbers. A weak aspect of the chapter is that momentum transfer (drag) is not handled in as comprehensive a way as heat and mass transfer—it is taken as understood that suitable information (e.g., drag coefficient, slip velocity, etc.) is obtainable from other sources or analyses. While this is certainly true, and monographs exist which treat this problem in some depth (at least for rigid spheres), readers will likely notice the lack of symmetry in treatment of the three exchange terms.

Chapters 4 and 5 deal with the difficult task of spanning the gap between single droplet studies and sprays. Chapter 4 begins this process by discussing work to date on droplet arrays of fixed geometry. Approaches based upon both simplified treatments and full Navier-Stokes solutions are discussed with an eye toward establishing how the single-droplet results of the previous chapter must be modified due to longitudinal or lateral interaction between the drops. Less detailed group or cluster models are also reviewed and the relative roles of the two approaches in providing insight into general spray phenomena are discussed. Chapter 4 closes with a brief discussion of drop-drop and drop-wall collision effects.

Chapter 5 completes the transition to sprays by giving the three basic approaches to dealing with spray modeling: interpenetrating continua, discrete particle tracking, and PDF transport (a.k.a., the spray equation). Besides providing the requisite background to understand each approach, Sirignano discusses the relationship between them and points out how, due to the hyperbolic nature of the droplet transport equations, Lagrangian as well as Eulerian methods can be, and have been, used successfully to obtain solutions for the dispersed phase. One limitation of the discussion is that modifications required to accommodate droplet source terms (nucleation, breakup, coalescence) are not included in any of the models discussed.

Chapters 6 and 7 treat computation of a number of spray problems. Chapter 6 recounts experiences and tradeoffs in obtaining accurate and efficient solutions, while Chapter 7 focuses on the results of a series of computations of increasing complexity. Of particular note in Chapter 6 is the discussion of the limitations of the point-source approximation commonly used in CFD codes for dilute sprays. The spray calculations treated in Chapter 7 are geometrically simple and provide a good example of the effects of progressively increasing complexity. One area in which this chapter falls short, however, is that it does not provide an example of a true state-of-the-art calculation in terms of overall complexity since neither turbulence nor particle source terms are included.

Chapter 8 treats particle-turbulence interaction. It begins with a brief review of current thinking about the conditions under which

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each phase can influence the other and proceeds through a review of two canonical particle-turbulence interaction problems: oscillatory rectilinear flow and vortex-drop interaction. Preparatory to these examples, the Maxey/Riley particle equation of motion (and its predecessors such as the BBO equation, etc.) is (are) discussed and extensions to finite Reynolds and Sherwood numbers are considered. As mentioned above, one of the very few weaknesses of the monograph is the less-detailed treatment of momentum transfer as opposed to heat and mass transfer. This criticism is alleviated to some extent by the discussion surrounding the Maxey/Riley equation, but the reviewer still questions whether it might be more effective pedagogically to move this discussion to the beginning of the monograph and to expand its scope.

The final chapter, Chapter 9, treats issues associated with high-pressure spray combustors. Specifically, it discusses near-critical-point phenomena, the increased importance of secondary breakup effects as critical conditions are approached, and the potential of molecular dynamics to treat some of these issues. The discussion of critical-point phenomena is self-contained yet provides an extensive listing of recent research on the topic. The discussion of secondary breakup is useful and important to the present topic, but tends to underscore the lack of a more general discussion of this phenomenon as another of the few components lacking from the text. The discussion of molecular dynamics is appropriate given its emerging role in both near-critical spray combustion and in understanding the dynamics of droplet coalescence and breakup.

Overall the monograph provides a very useful and comprehensive review of the challenges presented by droplet and spray problems. It complements the classic monograph of Clift, Grace, and Weber, *Bubbles, Drops, and Particles* (1978), updating the analysis methodology and state of knowledge for individual particles and providing a significant extension into the multiparticle arena by treating arrays, clusters, and sprays. While certain important topics are intentionally omitted—most notably, the effects of deformation on exchange rates and the effect of particle source terms on spray modeling—the text is sufficiently fundamental and complete to be a resource of lasting value for those working in the area.

Fluid Dynamics and Transport of Droplets and Sprays, by William A. Sirignano, Cambridge University Press, New York, 1999.

REVIEWED BY GRETAR TRYGGVASON[1]

[S0098-2202(00)03101-1]

It is easy to make the case for a book on the behavior and properties of sprays. Considerable part of the energy need of mankind is met by burning liquid fuels—almost always by atomizing it first—and other applications are in abundance. Professor Sirignano has contributed in major ways to our current understanding of sprays, both by his own research as well as by his mentoring of many younger spray investigators. In this book, he provides an up-to-date review of modeling of sprays. The book is very much a modeler's account of spray research and relatively few experimental results are presented or discussed. The book is also heavily—but not exclusively—based on the author's own research.

The book is divided into nine chapters, of which the first is a short introduction. The combustion of a single drop is then treated in chapters 2 and 3. The emphasis is on models of varying degree of complexity, starting with a discussion of a stationary drop and then adding convective effects. Chapter 2 ends with a short discussion of the effect of radiation and oscillations. Chapter 3 treats drops consisting of multicomponent liquids, metal-slurries, and emulsified fuels. In chapter 4, various ways to account for the presence of many drops and their interactions are examined. Detailed numerical simulations of well-defined problems are used to provide insight and models are developed for practical situations. The chapter ends with a discussion of droplet collisions and collisions of drops with walls. In chapter 5, continuum equations for the evolution of sprays are developed. The spray is treated either in an Eulerian or a Lagrangian way and the equations developed in chapters 2 and 3 serve as subgrid models for unresolved scales. In chapter 6, titled Computational Issues, various ways to solve the equations presented in chapter 5 are discussed. This is perhaps the weakest part of the book. It is apparently based on work done over fifteen years ago and no mention is made of parallelization or multigrid methods, for example. Chapter 6 does, however, contain a very valuable discussion of the accuracy of the point drop approximation. In chapter 7, computations of several complex, yet idealized, situations are presented. The flow is relatively simple and the focus is on the combustion. Only one- or two-dimensional problems are examined. The last two chapters discuss the state-of-the-art of research on droplet interactions with turbulence and vortical structures and droplet behavior at nearcritical, transcritical, and supercritical conditions. Both topics are currently under active study and the reader is provided with a good introduction to the current status and challenges of research in these areas.

Overall the discussion is clear and the material accessible. The author uses either analytical results or fairly detailed numerical simulations to provide the reader with insight, but the ultimate goal is to derive models that can be computed efficiently and used in numerical codes. In a field as rich as sprays, it is impossible to cover everything in a single book and the author has elected to focus on certain topics. A reader looking for experimental data, practical examples, or atomization will have to look elsewhere. Since a number of books treating other aspects of sprays have appeared recently, this is not a problem. My only complaint about the book is that I found the writing somewhat uneven. While the text often flows smoothly, some sections seem to have been completed in a hurry.

The book is certainly a welcome addition to the literature on modeling of sprays. It is a required reading for any student of spray combustion and—at least at the time of this writing—it brings the reader to the state-of-the-art of many aspects of spray research. The book can be used as a textbook for a graduate course on sprays and spray combustion, although it may be necessary to supplement it by more extensive description of atomization and by more examples of practical applications.

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