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The role of separation of scales in the description of spray combustion

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Abstract

The present paper deals with the description of the interacting multiscale processes governing spray vaporization and combustion downstream from the near-injector atomization region in liquid-fueled burners. One of the main objectives is to emphasize the progress made in the mathematical description and understanding of reactive spray flows by incorporation of rationally derived simplifications based on the disparity of length and time scales present in the problem. In particular, we aim to show how the disparity of the scales that correspond – with increasing values of their orders of magnitude – to the droplet size, interdroplet spacing, and width of the spray jets, ensures the validity of their homogenized description. The two-way coupling associated with exchanges of mass, momentum, and energy between the gas and the liquid phases is dominated by the homogenized exchanges with the gas provided collectively by the droplets, and not by the direct interaction between neighboring droplets. The formulation is used as a basis to address nonpremixed spray diffusion flames in the Burke-Schumann limit of infinitely fast chemical reactions, with the conservation equations written in terms of chemistry-free coupling functions that allow for general nonunity Lewis numbers of the fuel vapor. Laminar canonical problems that have been used in the past to shed light on different aspects of spray-combustion phenomena are also discussed, including spherical spray clouds and structures of counterflow spray flames in mixing layers. The presentation ends with a brief account of some open problems and modeling challenges.

Keywords: Separation of scales; Spray combustion; Liquid-fueled propulsion; Multiphase flows

1. Introduction

The existence of length and time scales of very different magnitude is a complicating characteristic of many problems encountered in fluid mechanics and combustion. The mathematical description of the associated flows can be facilitated by accounting for the disparity of these scales. A renowned example of the success of this approach is the boundary-layer theory developed by Ludwig Prandtl over a century ago. Separation of scales has also been extensively used in connection with the description of combustion problems, where the disparity of time scales is often due to the strong temperature sensitivity of the chemical

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reactions. For spray combustion, additional length and time scales originate from the two-phase nature of the flow.

Over the past half century combustion modelers have successfully exploited the separation of the scales present in the vaporization and combustion of droplets and sprays to generate simplified equations for the description of reactive spray flows. The purpose of this topical review lecture is to give an overview of the progress achieved and to describe some recent results. The presentation will begin with a discussion of the reasons for the validity, and also the shortcomings, of the continuum description of the gas and liquid phases in the vaporization and combustion of sprays. Because of the important role of the interphase exchange rates of mass, energy, and momentum, a summary of these rates is given, and then used in the conservation equations for the description of reacting sprays; this simplifies in the important extreme limiting cases of pure spray vaporization, without chemical reactions, and diffusion-controlled spray combustion. Simple laminar canonical problems, widely used in the past in fundamental investigations of spray combustion, are formulated in nondimensional form to identify the parameters that characterize the interplay of the different spray physicochemical phenomena.

Substantial research efforts have been made in the past in connection with the problems of vaporization and combustion of droplets and droplet arrays [1–9], ignition of fuel sprays [10], and dynamics and modeling of turbulent sprays [11–13]. Related work on atomization of liquid jets [14–16] and on the dynamics of particle-laden turbulent flows [17–19] is relevant for understanding the generation and dispersion of sprays. A reference book including an updated comprehensive presentation of the current level of understanding of fluid dynamics and transport of droplets and sprays is available [20]. In addition, other relevant literature include reference textbooks on atomization [21] and multiphase combustion [22], as well as research monographs [23,24].

The design of liquid-fueled combustion systems is subject to a number of constraints stemming from the need to vaporize the droplets, mix the fuel vapor with the surrounding air, and ignite and burn completely the resulting mixture in the limited available residence time, with the scales and parameters of these different physicochemical processes entering in the determination of the combustor performance. An important consideration that must be taken into account when describing vaporization and combustion in diesel engines, and also in the primary combustion zone of gas turbines, is the large value of the liquid-to-gas density ratio, on the order of a few hundred in many applications. Also relevant for combustion is the large value, of order $S \sim 15$, of the mass of air required to burn in stoichiometric proportions the unit mass of fuel. Another basic consideration pertaining to the required dispersion of the droplets in the combustion chamber is that the heat needed for the vaporization of each droplet comes from the sensible heat of the gas within the spray, so that vaporization in the bulk of the spray can only start when sufficiently dilute conditions are reached; otherwise the amount of gas entrained by the spray is insufficient to provide the heat of vaporization. In assessing the coupling between the liquid and gas phases, one must also bear in mind that the heat released by burning the fuel is enough lo lead to flame temperatures several times larger than the initial liquid temperature.

The large temperature sensitivity of the combustion reactions also enters in a fundamental way. For instance, in continuous-combustion devices this temperature sensitivity explains the onset of ignition near the hot boundary in mixing layers separating the spray from the preheated air. An important consideration, relevant for the selection of the atomizer in a given application, is that the droplet size must be small enough to ensure their complete vaporization and prevent their impingement with the confining walls. In view of the above considerations, it is clear that spray combustion stands out as a very particular category within the general field of two-phase flows, one that cannot be understood without accounting for its distinctive attributes.

The remainder of this paper is organized as follows. Some general comments concerning the specific characteristic of spray flows in combustion applications are given in Section 2, followed in Section 3 by a homogenized formulation for spray combustion that will serve as analytical framework for the rest of the paper. A qualitative description of spray combustion phenomena is presented in Section 4. The limit of infinitely fast chemical reaction is considered in Section 5, which provides a general Burke-Schumann formulation for the computation of spray flames. Sections 6 and 7 are devoted to the characterization of elementary spray structures. The final section outlines some of the open problems in spray combustion, including modeling issues.

2. Preliminary considerations pertaining to spray flows in combustion systems

2.1. Atomization in spray-combustion applications

The reduction in spray length required by the limited size of the combustion chamber can only be accomplished when there exists a significant velocity difference between the liquid jet or sheet to be atomized and the surrounding coflowing gas [21]. This is the case if the liquid stream is