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Forced ignition of turbulent spray flames

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Abstract

This paper reviews the current state of knowledge on the initiation of a flame in a spray through the action of a spark or through local deposition of heat, and the subsequent flame development, in uniform and non-uniform dispersions of droplets and in the presence of turbulent flow. These processes are of importance in various applications such as gas turbine ignition (relight) and safety related to flammable liquid mists. The review focuses on the initial kernel development, the evolution of a spherical or edge flame, and the ignition of the spray flame when viewed at the whole combustor scale. The factors that determine success or failure of the ignition process at the various phases of the overall burner ignition are discussed through experiments and Direct Numerical Simulations, while modelling efforts are also assessed. The fuel volatility, droplet size, overall fuel-to-air ratio, and the degree of pre-evaporation are the important factors that distinguish spray ignition from gaseous flame ignition, and the extra fluctuations introduced by the random droplet locations, and how this may affect modelling and flame evolution, are highlighted. The flame propagation mechanism in laminar and turbulent sprays is one of the key aspects determining overall ignition success. Suggestions for future research are discussed.

Keywords: Forced ignition; Spark; Spray; Relight; Ignition probability

1. Introduction

The initiation and subsequent complete establishment of combustion in a spray due to an externally-imposed means, such as an electrical or laser-induced spark, a plasma jet, or a heated surface, is here denoted as *forced ignition* and is reviewed from the perspective of the various temporal and spatial scales and the stochasticity of the underlying phenomena. This knowledge is not only of fundamental interest, but also of practical importance for a range of applications. One of these is the ignition in a gas turbine combustor. Especially for aviation gas turbines, the need to ensure ignition in the event of a flame extinction determines, to some extent, the operating envelope of the airplane and also the volume of the combustor. This, in turn, has implications for the weight, cost, and emissions of the engine. The need to be able to predict, at the design stage, the ignitability of a gas turbine combustor would be advantageous, but is limited at present by the complexity of the phenomena. As another example, we mention the danger of ignition in mists of a flammable liquid, where

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the assessment of an explosion hazard is not easily carried out in the absence of information on the ignition itself, but also the subsequent flame speed and the factors that affect both. This paper aims to review the present state of our knowledge on these topics, mostly from the point of view of the fundamentals behind spark ignition processes in spray systems and focusing on the effects of the spray and the turbulence on the initiation and evolution of the flame.

It is very important to distinguish the different phases involved in the ignition of a spray flame. These different phases can be summarised as follows [1,2]:

1. Kernel generation
2. Flame growth
3. Burner-scale flame establishment

The boundaries between these phases are not always clear and this is amply manifested by the different interpretations given to the term *ignition* in the literature. We could loosely define as *kernel* the leftover once a spark has stopped delivering energy and in this paper we focus on the fluid mechanical rather than the very quick plasma-related timescales. This kernel would normally be small, of the order of the spark size. The flame growth would normally occur over lengthscales of the order of the integral lengthscale and over timescales comparable to some bulk flow timescale. The third phase, full burner ignition, is obviously specific to each geometry studied, but due to the predominance of recirculation zones in most combustors of practical interest, this configuration must specifically be considered. The first two phases, in the specific context of sprays, are discussed in this review separately, to the extent possible. The third phase has received special attention recently from the perspective of ignition probability in flames stabilised by recirculation zones [3,4] and is also discussed. There is a fourth phase, called *light-round*, that focuses on the flame propagation from burner to burner and is important for gas turbines with annular combustion chambers. This phase is quite configuration-specific and is discussed very briefly in Section 4. The three phases mentioned above are present in all flame types (premixed, non-premixed, spray, swirl vs. no swirl, etc.). Due to the turbulent nature of the flows considered, the flow, mixing, and spray patterns at the locality and instant of the spark will be different at different realisations (e.g. at different spark events), and so we may expect significant variability in the result of individual spark events. The stochastic nature of the ignition process in turbulent burners is therefore important to consider and forms a significant focal point of our discussions.

We begin with a classification of the various configurations and canonical problems that are important to study before we build the full picture of the overall turbulent spray flame ignition. We review some fundamental findings revealed by experiment, DNS, and modelling on forced ignition in turbulent non-premixed systems with gaseous fuels that are needed for understanding spray ignition, focusing on the stochastic behaviour and the range of temporal and spatial scales involved. We continue with the separate discussion of the various phases of kernel generation, flame propagation, and overall flame establishment in spray systems, and we consolidate some of the physics by discussing in Section 4 the particular application of gas turbine relight. Some comments on modelling are included in Section 5.

2. Classification and key concepts

2.1. Autoignition vs. forced ignition, kernel vs. flame, and relevant scales

The canonical problem of autoignition of a single droplet in an infinite, stagnant hot oxidiser has been reviewed by Aggarwal [5], and discussed in the context of mixture fraction space in Ref. [6], while the autoignition of turbulent gaseous non-premixed and spray systems (with less emphasis on the latter) has been reviewed by Mastorakos [1]. *Autoignition* must be distinguished from *forced ignition*: in the former, one or both of the reactants (but usually the oxidiser) are already at a high enough temperature for chemical reactions to proceed. The time of ignition or *ignition delay time* (defined, loosely, as the instant when the temperature rises close to its highest value) and the possibility that autoignition is impeded completely are determined not only by the pressure, the initial temperature, and the relevant chemistry, but also by mixing patterns and scalar gradients and their fluctuations [1].

In the forced ignition case, the initial condition is essentially chemically frozen and it is the deposition of energy and/or radical species that raises the temperature high enough, quickly enough, and in a region wide enough for combustion to begin and provide a self-sustaining flame. The spark (treating it either as a heat source or as a radicals source or both) eventually raises the temperature enough for autoignition to proceed; the corresponding ignition delay time is usually very fast or comparable to the spark timescale. Sometimes, failure to ignite can be traced to the slowness of this autoignition process, for instance if the temperature was not raised high enough in case, for example, of a weak spark, or if a substantial portion of the spark's heat is removed by stretch, as through intense turbulence or a very small spark. Let us call this the *first* or *short mode of ignition failure*.

Very often in applications sparks are large and powerful and succeed to initiate a kernel. Perhaps therefore more relevant to practice is the failure to ignite (in a full-burner sense) because a