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Numerical investigation of kerosene single droplet ignition at high-altitude relight conditions

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ABSTRACT

In this study, the fundamental problem of the ignition of a kerosene single droplet in a quiescent medium at engine high-altitude relight conditions is investigated using numerical simulations. The main objective is to improve the understanding of ignition phenomena with a focus on the effect of droplet evaporation in determining the growth of the ignition kernel and flame establishment. Results show that when the droplet is fully immersed in a high temperature region, ignition occurs when the scalar dissipation rate associated with evaporation decreases enough to allow the initiation of a flame. The ignition time depends on the droplet diameter and the far field temperature, i.e. the position of the droplet with respect to the spark location. As the fuel is consumed, the flame is found to move closer to the droplet surface until the flame cannot sustain itself any more due to increasing scalar dissipation rates. Furthermore, results show that at very low temperatures typical of high-altitude relight conditions no flammable mixture is available around the droplet. Therefore, the success of an ignition event mainly depends on the energy released by the spark and the rate at which this energy is diffused toward the droplet surface to enhance the evaporation rate and create a flammable mixture. The findings are analysed from the perspective of gas turbine applications.

1. Introduction

An important requirement for aviation gas turbines is the capability to safely reignite after a flameout during the flight. This problem, usually referred to as *high-altitude relight*, involves the *forced ignition* of a spray at low pressure and low temperature conditions. Assuring high-altitude relight is a strong constraint on the design choices of engine manufacturers that has an impact on the engine weight and even on the operating envelope of the entire airplane. For this reason, the problem of spray ignition at high-altitude relight conditions has gained increasing attention.

Compared to gaseous mixtures, the ignition process of spray flames is significantly more complex due to the different scales and phenomena introduced by the presence of liquid fuel droplets [1]. Different ignition modes can be distinguished depending on the scale of the flame relative to the droplet dimension. Droplet ignition implies the formation of a flame around the droplet, or in its wake region if convective transport is present, whereas spray ignition represents the appearance of a flame involving the entire spray with a characteristic dimension of the flame larger than the droplet size. The intermediate case is represented by droplet cluster ignition where a flame around clouds of droplets is generated. In all these modes, ignition is preceded by the evaporation of fuel droplets and the formation of a flammable mixture followed by kernel initiation and flame growth and establishment. As also pointed out in the recent review by Mastorakos [1], fuel volatility, droplet size and degree of pre-evaporation are important factors that distinguish spray ignition from gaseous flame ignition [2].

Kernel formation and flame growth in turbulent spray flames has recently been investigated using Direct Numerical Simulations (DNS) [3–6]. In all these studies the droplets were considered as Lagrangian particles with point source approximation and, therefore, the droplet scale fuel distribution was not accurately resolved. Nevertheless, very interesting phenomena can still be observed and insight into the mechanism of flame initiation and establishment can be gained. From all these studies it is clear that the ignition of spray flames is strongly affected by the characteristics of the spray and evaporation phenomena. As also discussed in Ref. [7], a key parameter is the fraction of fuel that has been evaporated which depends on the energy released by the spark and the diameter of the droplets in the spark region. A spray population with smaller diameter generally requires lower energy for ignition due to the faster evaporation. In some cases [6], it has been shown that the deposition of the spark energy is followed by the formation of single

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droplet flames that eventually merge to give rise to a flame at the spray level. The formation of stoichiometric mixture bridges between the droplets is also an important phenomenon for flame propagation and has received increasing attention [8]. It is important to point out that a successful kernel generation does not necessarily require the presence of flammable mixture at the spark location. A spark located outside of the nominal flammable region may result in a successful kernel generation if enough energy is diffused to the flammable region to cause ignition there [9]. The timescales associated with evaporation and the local evaporative cooling play an important role for the success of the initial kernel formation, but also for the subsequent flame growth and insufficient evaporation (fuel starvation) may lead to flame extinction even if a kernel was generated successfully [1].

Droplet size and the degree of pre-evaporation can be even more important at high-altitude relight conditions where the low temperature results in a very slow evaporation process and, therefore, strongly affects the availability of fuel in the region of the spark. Once the flame has extinguished, the low temperature environment together with a poor atomization (due to lower air flow rates) may cause a significant decrease in the amount of fuel that has evaporated implying the need of a larger amount of spark energy to initiate the flame kernel and to produce a self-sustaining (propagating) flame [10]. Experiments in model combustors (e.g. [10–13]), usually focused on the effects of spray parameters, such as droplet mean diameter, fuel type, air pressure and temperature, have shown that a small mean droplet diameter and high fuel volatility generally increase the capability of flame ignition and stabilization in the combustor. Furthermore, the formation of a stable flame in the whole combustor usually happens with a given delay, due to both evaporation, flame initiation and propagation [11].

The objective of this study is to improve the understanding of forced ignition at high-altitude relight conditions with emphasis on the role of evaporation in determining the growth of the initial kernel and flame establishment. The fundamental case of kerosene single droplet ignition in a quiescent medium is considered and studied by means of numerical simulations with detailed chemistry and fuel modelled as a multi-component surrogate. The use of a quiescent (or nearly quiescent) configuration allows us to avoid additional complications arising from convective and turbulent transport and, therefore, to focus on the effects of evaporation and diffusion in the droplet near field. Although this study directly investigates single droplet ignition, it could also be relevant for spray ignition. As previously pointed out, it has been observed that the formation of the initial kernel can proceed through the formation of flames at the droplet scale that develop into a spray flame. Therefore, the single droplet case might be useful to give further insight into the first stages of the kernel development also in the more general case of spray combustion. Furthermore, the detailed solution of the droplet near field can complement the DNS studies that do not resolve the field close to the droplet surface due to the point approximation for the droplets.

The paper is organized as follows. First, the case of droplet evaporation under low pressure and temperature conditions is investigated. Then, droplet ignition results are discussed. The case of a spark much larger than the droplet diameter is considered as representative of typical aero-engine ignition processes. The effect of droplet diameter and temperature in the spark region on the mixture formation and initiation of the flame is studied. The more fundamental case of a spark located in the vicinity of the droplet surface is also considered to highlight the role of energy diffusion and evaporation in determining conditions in the droplet near field favourable for ignition. Conclusions and recommendations for future work close the paper.

2. Methodology

The fundamental case of an isolated droplet in the absence of any convective motion other than Stefan flow has been considered. This canonical case has received a lot of interest in the literature [14–16] and is further investigated here in the context of forced ignition of kerosene droplet at high-altitude relight conditions. An ambient pressure equal to 0.3 bar was considered here as representative of high-altitude conditions with the lowest ambient temperature equal to 250 K. Chemical reactions were modelled using a detailed kinetic mechanism developed for kerosene by Dagaut and Cathonnet [17,18] with 209 species and 1673 reversible reactions, and reaction rates recommended for 1 atm. According to this mechanism, the kerosene fuel consist of a surrogate of three components, with the following molar composition [17]: 74% n-decane (n-$C_{10}H_{22}$), 15% n-propylbenzene (PH-C_3H_7), and 11% n-propylcyclohexane (CY-C_9H_{18}).

The liquid droplet was modelled as a three-component fuel, replicating the kerosene surrogate composition considered in the chemical mechanism. The single droplet ignition behaviour was investigated using the code described and validated in Refs. [15,16,19], in which the unsteady transport equations of mass, energy and species in spherical coordinates are simultaneously solved for both the gaseous and liquid phases according to the algorithm described by Cho et al. [20]. Details regarding the implementation of the multi-component solver can be found in Ref. [16], whereas the interested reader is referred to Refs [15,19] for more details on the code and the solution algorithm. Additional information about the equations can also be found in Ref. [20]. Properties of the three liquid components were modelled as detailed in Ref. [16].

The case of a droplet suddenly immersed in hot air was considered here as representative of a spark much bigger than the droplet diameter. Considering that the typical dimension of a spark are few mm (or even cm) while the droplet diameter is generally below 0.1 mm, this assumption appears reasonable, at least as a first approximation. Values of the air temperature T_{air} in the range from 1300 to 2000 K have been investigated to simulate the behaviour of a droplet located both in the spark region (high T_{air}) and in the region surrounding the spark that is heated up by the diffusion of spark energy. A pure evaporation case at low temperatures $T_{air} = 250$ K, typical for high-altitude relight conditions is also investigated. Simulation for pure evaporation cases were performed without activating the chemical source terms.

The diffusion of spark energy in the droplet near field and its effect on the evaporation and mixture field has also been investigated through an idealised case, where a heat source was placed at a given radial position r_{spark} measured from the centre of the droplet. Due to the assumption of spherical symmetry, this "spark" is effectively shell-shaped, engulfing the droplet. While this is not a realistic geometry, the investigation is useful from an academic perspective, since it allows to explore how thermal diffusion of spark energy can lead to ignition. The spark is modelled as a source term in the energy equation. In physical space this heat source has a Gaussian shape (as a function of the radius), centred on r_{spark} with a characteristic width $w_{spark} = 2\sigma_{spark}$ and a peak value E_{spark}. A constant spark source is applied after a given evaporation time t_1 for the duration τ_{spark}. These simulations also help quantify the evaporation time τ_{evap} as a function of ambient conditions.

The same numerical set-up described in Ref. [16] was used in this work. The droplet and gas phase were discretised with 600 and 300 nodes respectively. Pure air at a given temperature was imposed at the far-field boundary (located at a distance $r/r_{d,0} = 100$, where r is the radial coordinate and $r_{d,0} = d_0/2$ is the initial droplet radius), whereas an initial diameter and temperature were assigned to the droplet. A droplet temperature equal to 300 K was used in all cases with exception of the simulation with $T_{air} < 300$ K where the initial droplet temperature was set equal to the ambience temperature. Both the droplet and the gas phase were initialised with uniform temperature and composition. Exponential fitting was used to initialise the gas phase close to the droplet surface, in order to smooth out the transition from the droplet interface to the far-field conditions and, therefore, improve the convergence of the code in the first steps of the simulation.

In the presentation of the results, the *mixture fraction* will be used quite often to show the mixing behaviour in the droplet near field. Here,