Review

Single droplet ignition: Theoretical analyses and experimental findings

Suresh K. Aggarwal[*]

Department of Mechanical & Industrial Engineering, University of Illinois at Chicago, 842 W. Taylor Street, Room 2021, Chicago, IL 60607-7022, United States

ARTICLE INFO

ABSTRACT

Spray ignition represents a critical process in numerous propulsion and energy conversion devices. Compared to a gaseous mixture, ignition in a spray is significantly more complex, as the state of ignition in the latter case can be defined by three distinct ignition modes namely, droplet ignition, droplet cluster ignition, and spray ignition. Ignition for an individual droplet represents the appearance of a flame surrounding the droplet or in the wake region, with a dimension on the order of droplet diameter. The cluster or group ignition refers to the ignition around or inside a droplet cloud, while the spray ignition implies the appearance of a global flame with a characteristic dimension few orders of magnitude larger than a droplet. In all three modes, ignition is preceded by the evaporation of fuel droplets, formation of a combustible gaseous fuel−air mixture, and initiation of chemical reactions producing sufficient radical species. The identification of the dominant ignition mode for given two-phase properties represents a problem of significant fundamental and practical importance. Research dealing with laminar and turbulent spray ignition has been reviewed by Aggarwal [1] and Mastorakos [2], respectively, while Annamalai and Ryan [3] have provided a review of droplet group combustion/ignition. In the present review, we discuss experimental, theoretical, and computational research dealing with individual droplet ignition. Topics include the quasi-steady and unsteady models for the ignition of a fuel droplet in a stagnant environment, the droplet ignition in a high-pressure environment, the convective effects on droplet ignition, and multicomponent fuel droplet ignition. Studies dealing with the two-stage and NTC ignition behavior for a droplet are also discussed. Finally, relationship between the droplet ignition mode to droplet cluster and spray ignition modes is briefly described. Potential topics for further research are outlined.

© 2014 Elsevier Ltd. All rights reserved.

Contents

---

* Tel.: +1 312 996 2235.
  E-mail address: ska@uic.edu.

Nomenclature:

a_F	fuel exponent
a_O	oxygen exponent
B'	preexponential factor in Arrhenius rate expression
c_p	specific heat
d_0	initial droplet diameter
E'	activation energy
Le	Lewis number
M	non-dimensional burning rate
p	non-dimensional pressure
Q'	heat release per unit mass of fuel consumed
r	non-dimensional radial coordinate $= r'/r'_s$
r_s	instantaneous droplet radius $= r'/r'_{so}$
R_u	universal gas constant
t	non-dimensional time
T	non-dimensional temperature $= c'_p T'/Q'$
T_s	non-dimensional surface temperature
T'_a	activation temperature ($^\circ$K)
W	molecular weight

X	mole fraction
Y	mass fraction

Greek letters

λ	thermal conductivity
ν	stoichiometric coefficient
ρ	density
σ	stoichiometric oxidizer/fuel ratio

Subscripts

f	fuel
L	liquid phase
o	oxidizer
p	product
s	droplet surface
∞	ambient (at infinity)

Superscripts

$'$	dimensional variable

1. Introduction

Liquid spray combustion is employed in industrial furnaces, boilers, gas turbines, diesels, spark-ignition, and rocket engines. Ignition represents a crucial event in the operation of these systems. It is followed by the appearance of a flame, which then propagates at the local flame speed into the spray or two-phase mixture or gets stabilized depending upon the mixture conditions. Ignition of a fuel spray in a jet engine combustor is an important process due to the desirability of fast and reliable ignition under a wide range of conditions, and its relation to the issues of flame stabilization and transient combustion. Similar considerations apply to direct-injection spark ignition engines, in which a fast, well-controlled ignition is important to engine efficiency and emissions. In a diesel engine, the self-ignition of fuel sprays injected into a high-temperature and high-pressure environment represents a critical event in their operation. Spray ignition research is also motivated by the safety considerations in various systems, in which the ignition must be avoided. Examples include explosions in mines and industrial settings, fire safety in earth and space environments, and prevention of autoignition in the mixture delivery system of prevaporized-premixed gas turbine combustors.

Compared to a gaseous mixture, the ignition process in a spray is significantly more complex, as the state of ignition in the latter case can be defined by three distinct ignition modes, namely, droplet ignition, droplet cluster ignition, and spray ignition. In all three modes, ignition is preceded by the evaporation of fuel droplets, formation of a combustible gaseous fuel–air mixture, and initiation of chemical reactions producing sufficient radical species. These processes are determined by the local and global spray properties, which include temperature, pressure, overall and local equivalence ratios, and other gas and dispersed phase properties. The ignition of an individual droplet represents the appearance of a flame surrounding the droplet or in the wake region, with a dimension on the order of droplet diameter. An ignition event for a droplet distinguishes the state of pure vaporization from that of a diffusion flame around the droplet. This has implications for spray combustion with regard to flame stability and amount of pollutants formed. In spray combustion modeling, the identification of this event is important since it determines the amount of heterogeneous

burning involved, and the rates of mass and heat transport are significantly altered following its occurrence. A common droplet ignition situation, which has received the most attention, involves the ignition or autoignition of an isolated droplet in a hot, oxidizing environment, although some experimental studies have also employed an electric spark to ignite an individual droplet. The ignition time is defined as the time from the instant a droplet is introduced into the hot environment to the instant a flame is detected in the vicinity of the droplet.

The ignition of a liquid fuel spray, on the other hand, represents the appearance of a global flame that is associated with the whole spray, and has a characteristic dimension few orders of magnitude larger than a droplet. Spray ignition may be initiated by an external source, such as an electric spark ignition in gas turbine combustors and spark-ignition engines, or without any localized ignition source, i.e., spontaneous ignition such as in a diesel engine. The introduction of an electric spark creates a localized region of intense droplet vaporization, high reactivity and heat release. This region, which is commonly referred to as an ignition kernel, involves several evaporating droplets. During the spark duration, the temperature in the ignition kernel increases sharply, but then decreases due to vaporization and heat losses to the surrounding. As the chemical activity intensifies and the heat-releasing reactions are initiated, the temperature starts increasing again, and the inflection point in the temperature time history is often used to identify the occurrence of ignition. Spontaneous spray ignition involves introduction of a two-phase mixture into a high-pressure, high-temperature, oxidizing environment. The concept of an ignition kernel is generally not employed here though it may be applicable in several autoignition situations. The ignition delay is generally defined as the time interval between the creation of a combustible mixture and the "appearance" of a flame. In a diesel engine, it is defined by the time interval between the start of fuel injection and the appearance of a flame as detected by sharp rise in temperature or OH species concentration. In this case, the ignition location is also an important property that strongly affects flame stabilization [4,5] and engine combustion and emissions. The ignition of a droplet cloud or cluster [3] represents an intermediate situation, and can be utilized to bridge the results of studies dealing with the other two ignition modes. Here also, a typical physical