Fuel 222 (2018) 733–742

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

Linear stability analysis of laminar premixed water-in-fuel emulsion spray flames

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ARTICLE INFO

Keywords:
Water-in-fuel droplets
Spray
Premixed laminar flame
Stability analysis

ABSTRACT

This paper considers the stability of a laminar water-in-fuel spray premixed flame. The droplets of the spray are comprised of two immiscible components viz. water and fuel, with the water being contained within an outer liquid shell of fuel. The fuel and water evaporate sequentially. Due to its relatively large latent heat of vaporization the water vapor acts to cool the flame that is sustained by prior release of fuel vapor. To simplify the inherent complexity that characterizes the analytic solution of multi-phase combustion processes, the analysis is restricted to fuel-rich laminar premixed water-in-fuel flames, and assumes a single-step global chemical reaction mechanism. Steady-state solutions are obtained and the sensitivity of the flame temperature and the flame propagating velocity to the initial water content of the emulsion droplets is established. The linear stability analysis revealed an increased proneness to cellular instability induced by the presence of increased water content of the emulsion droplets. A similar effect was noted for the neutral pulsating stability boundaries.

1. Introduction

It is common knowledge that tremendous effort is currently being invested in the search for viable biofuel blends for combustion engineering in an effort to reduce harmful NOx and PM emissions to the atmosphere. This effort has been spurred on by increasingly stringent international protocols governing the restricted emission of harmful pollutants to the atmosphere (see, for example, [1]). In practical terms, biofuel blends must be created to be fit for utilization in existing combustors (such as jet engines, for example) thereby circumventing the need to perform expensive modifications to current combustors or, more critically, to designing new suitable combustors.

Of the many ideas being considered to attempt to meet the strict standards dictated by protocols is the use of water-in-fuel emulsions. Consideration of water-in-fuel emulsion (hereinafter referred to as WIFE) droplets for combustion involves understanding a number of aspects of the physical behavior of these droplets as they evaporate, in terms of processes occurring within the droplet and their impact on the immediate vicinity outside the droplet. As will be described it is these processes that are responsible for the benefits that the droplets potentially possess, which may be advantageously harnessed under appropriate operating conditions.

Kadota and Yamasaki [2] appear to be the first authors to present a review dedicated to theoretical and experimental research on water fuel emulsion combustion until the year 2002. Subsequently, in 2014, Khan et al. [3] reviewed current trends in water-in-diesel emulsion as a fuel. Their paper focuses exclusively on experimental studies that were carried out to investigate the physics of both NOx and particulate reduction and the phenomenon of micro-explosion that may occur under appropriate operating conditions in WIFE (see later). In addition, there is a discussion of research into the actual influence of water-in-diesel emulsions on engine performance for a wide range of engine types and loading conditions. It is of interest to note that, due to the variety of engine set-ups and experimental methodologies employed, results reported in the literature were not consistent. However, generally, a water content of between 5 and 40% by volume was successfully utilized. Although there was a consensus concerning the *ability* of the water-in-fuel emulsions to reduce NOx and particulate production the reported *extent* of the reduction was far from uniform.

The first models of emulsified water/oil droplets appeared in 1977 [4,5]. Jacques [4] solved numerically a heat transfer model containing essential elements of the underlying behavior of the transient heating of a single emulsified fuel droplet. His main concern was to try to quantify the primary effect of the water in the droplet. Attention was particularly focused on attempting to replicate the experimentally observed reduction of particulate formation by the water's presence based on the premise suggested by Shyu et al. [6] that, for waterless fuel droplets, this occurs during latter stages of heavy fuel oil combustion as a result of cracking of liquid phase hydrocarbons within the droplet at temperatures above 700 K. The addition of water was shown to act as an

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https://doi.org/10.1016/j.fuel.2018.02.113
Received 31 August 2017; Received in revised form 12 February 2018; Accepted 16 February 2018
Available online 23 March 2018

Nomenclature

A	pre-exponential constant
C_f,C_W	evaporation coefficients of fuel and water, respectively
c_p	specific heat
d_1,d_2	terms in Damköhler number expansion
Da	chemical Damköhler number
D	mass diffusion coefficient
E	activation energy
H	Heaviside function
k	wave number
l	$O(1)$ term in Lewis number expansion
L_f,L_W	non-dimensional latent heat of vaporization of fuel and water, respectively
Le	Lewis number
m^*, m	mass fraction and normalized mass fraction, respectively
q	heat of reaction
R	universal gas constant
s	mole fraction of oxygen in the fresh mixture
S_v	evaporation rate
t^*,t	time and normalized time coordinate, respectively
t_1,t_2	terms in temperature expansion
T	temperature
U	burning velocity
W	(dimensional) chemical source term
x^*,y^*,x,y	spatial and normalized spatial coordinates, respectively
α	initial water content in each WIFE droplet
α_1,α_2	stability analysis parameters, Eq. (85)
$\hat{\alpha}_{OF}$	stoichiometric coefficient
χ	stretched spatial coordinate
δ	delta function
$\tilde{\delta}$	total initial liquid load (fuel + water)
Δ	Laplacian (Eq. (29))
ε	small parameter
ϕ	perturbed flame front surface
φ	equivalence ratio
λ	thermal conductivity
σ	thermal expansion ratio
ρ	density
ω	perturbation frequency
ξ,η	normalized spatial coordinates
τ	normalized time coordinate
θ	normalized large activation energy

Subscripts and superscripts

a	adiabatic
b	burned value
dW	relating to water in droplets
df	relating to fuel in droplets
f	fuel
u	unburned value
W	water
O	oxygen
vf	value at onset of vaporization
–	relating to steady state solution
~	relating to perturbation
'	modified $O(1)$ quantities
*	dimensional dependent and independent variables

extra source for heat loss thereby lowering the temperature within the droplet so that the extent of cracking reactions (and, therefore, subsequent formation of particulates) was reduced.

Micro-explosions seem to have been first reported in 1965 [7]. Experimental studies showed that combustion of compound droplets with different volatile fluids may be accompanied by violent explosion of the droplets. As the temperature increases, the higher volatile fluid, which is strategically located at the core, will evaporate sooner in the form of a bubble. The fast expansion of the gas at the core will result in partial or full disintegration of the parent droplet and it is this behavior that is called a micro-explosion. A similar occurrence called puffing happens when the nucleation bubble ruptures the parent droplet along with fine steams of tiny droplets. This happens when the bubble expands very rapidly and tears through the host droplet at a specific location. These phenomena are very important to combustion because they provide a secondary mechanism of atomization by breaking down large droplets into a smaller, faster evaporating form. Since the fuel combusts in gaseous form only, micro-explosions help more fuel to change phase from liquid to gas, thereby improving the efficiency of fuel consumption. As the current work focusses on operating conditions under which microexplosions do not occur, we refer the interested reader to various studies of microexplosions. The literature covers experimental, theoretical and recent computational [8–13] investigations of single droplet behavior.

Due to the complexity involved in modeling WIFE spray combustion under conditions in which micro-explosions take place, all theoretical studies we are aware of have only been concerned with the sequential evaporation of the fuel outer “shell” followed by the evaporation of the water inner “core”. Thus, in a series of papers Hsuan et al. [14], Hsuan and Lin [15,16] and Hou et al. [17] considered WIFE spray flames. The mathematical analysis presented by these authors related to both fuel rich and fuel lean flames and took account of the fact that the major effect of the water evaporation was as a heat sink due to the heat loss incurred as the water absorbed heat for evaporation. Actually, such heat loss is also present when the outer fuel layer evaporates but the latent heat of evaporation of water is typically much larger than that of hydrocarbon fuels. For example, for n-octane it is of the order of 300 kJ/kg in comparison to 2254 kJ/kg for water. This discrepancy can have a strong effect on the laminar flame speed, depending on the relative amount of water in the droplets and the location of onset of pure water evaporation. With the respect to the latter both possible scenarios were examined (i.e. pre- and post- flame front water evaporation) combined with the nature of the fuel evaporation (completely before the flame front or only partially so). The methodology used was based on Lin et al.'s [18] analysis of fuel spray combustion which made use of asymptotic methods for finding the flame structure and an expression for the burning velocity. Critical conditions for flame extinction and propagation were determined as a function of the initial water content in the droplets.

An allied study, motivated by the behavior of emulsion explosives made up of a mixture of a fuel and an ammonium nitrate-water solution, was conducted by Hughes et al. [19]. A one-dimensional theoretical model was solved numerically to examine combustion waves driven by competing exothermic and endothermic reactions in the presence of water evaporation. A rich variety of influences of the water content on the flame propagation and its stability were noted, mainly because of its impact on the temperature and thereby on the fraction of ammonium nitrate consumed by the competing exothermic and endothermic reactions. Interestingly, the water evaporation was treated as a first-order chemical reaction with a specially constructed rate coefficient. However, once again, micro-explosions were not accounted for.

The purpose of the current paper is to establish a preliminary theoretical groundwork through which some physical insight can be gained into some of the mechanisms at play in laminar water-in-fuel spray premixed flame propagation. This will serve as a benchmark for comparison for the future aim of building a more complex and