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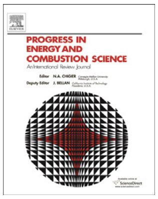

Review

Advances in droplet array combustion theory and modeling

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ABSTRACT

A review of research on the subject of the vaporization and burning of fuel droplets configured in a prescribed array is presented, including both classical works and research over the past decade or two. Droplet arrays and groups and the relation to sprays are discussed. The classical works are reviewed. Recent research on transient burning and vaporization of finite arrays with Stefan convection but without forced convection is presented, including extensions to non-unitary Lewis number and multi-component, liquid fuels. Recent results on transient, convective burning of droplets in arrays are also examined. In particular, transient convective burning of infinite (single-layer periodic and double-layer periodic) and finite droplet arrays are discussed; attention is given to the effects of droplet deceleration due to aerodynamic drag, diameter decrease due to vaporization, internal liquid circulation, and arrays with moving droplets in tandem and staggered configurations. Flame structure is examined as a function of spacing between neighboring droplets and Damköhler number: individual droplet flames versus group flames and wake flames versus envelope flames. Based on existing knowledge of laminar droplet array and spray combustion theory, experimental evidence, and turbulent studies for non-vaporizing and non-reacting two-phase flows, comments are made on the needs and implications for the study of turbulent spray and array combustion.

Contents

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Nomenclature

Latin letters

a	droplet radius in Figs. 7 and 8
B_M	spalding mass transfer number
B_H	spalding heat transfer number
C_D	drag coefficient
C_L	lift coefficient
c_p	constant pressure specific heat
D	diffusion coefficient
d	droplet diameter, also droplet spacing in Figs. 7 and 8
Da	Damkohler number
E_a	activation energy
h	specific enthalpy
k	turbulence kinetic energy per unit mass
L	latent heat of vaporization
L_{eff}	effective latent heat of vaporization
Le	Lewis number
M	molecular weight
$\dot{m}$	mass vaporization rate
N	number of droplets or mole number
Nu	Nusselt number
p	pressure
Pr	Prandtl number
$\dot{q}$	magnitude of heat flux
Q	heat of combustion
r	radial coordinate
R	droplet radius or universal gas constant
Re	Reynolds number
Re_0	initial Reynolds number
Re_m	modified Reynolds number, defined after Eq. (35)
s	droplet spacing
S	stoichiometric number
Sc	Schmidt number
Sh	Sherwood number
sp	droplet spacing
T	temperature
T_b	boiling temperature
t	time
U_d	velocity of the droplet
U'_∞	relative velocity between the air stream and the droplet
u	velocity
V_A	array volume
V_l	total liquid volume in array
$\vec{V}$	mass-averaged velocity vector
W	molecular weight
We	Weber number
X	mole fraction
Y	mass fraction
$\mathbf{1}$	unit tensor

Greek letters

α	thermal diffusivity
ε	mass flux fraction; also, turbulence kinetic energy dissipation rate
ζ	normalized radial coordinate
η_A	interactive-isolated vaporization ratio
θ	liquid volume fraction
λ	thermal conductivity
ν	stoichiometric mass ratio, fuel-to-oxidizer
ρ	density
τ_K	Kolmogorov time scale
τ_p	particle response time
ϕ	potential function
Φ	normalized potential function
σ_0	ratio of initial vortex radius to initial droplet radius
ξ	similarity parameter

Subscripts

avg	average value
eff	effective value
F	fuel vapor
film	film conditions (average of ambient and surface conditions)
g	gas phase
i	the ith species
iso	isolated droplet
j	integer index designating individual droplet in an array
l	liquid phase
lS	liquid surface
n	the nth species
O	oxygen
S	surface value
s	surface value
∞	ambient value
ε	mass-flux-averaged value
0	initial value

Superscript

$\hat{}$	average over gas phase
$\cdot$	dimensionless quantities
o	reference value

1. Introduction

The fuel-droplet and fuel-spray combustion literature has many research works addressing experimental and theoretical configurations where individual droplets are surrounded by their individual flames [1]. Yet, observers of practical spray flames find many droplets engulfed by a closed flame. Chigier and McCreath [2] observed such engulfment in the laboratory. More recently, Candel et al. [3] also found evidence that a thick flame shell surrounds portions of the spray. In this review, there will be a focus on a certain theoretical approach to understanding this phenomenon and the interactions amongst vaporizing droplets in a spray flame.

There are various classes of configurations where a collection of interactive vaporizing and burning droplets can be studied. Sirignano [1,4] classified interactive droplet studies into three categories: droplet arrays, droplet groups, and sprays. Arrays involve an experimentally or computationally manageable number of interacting droplets or a spatially periodic configuration with ambient gaseous conditions specified. There can be many droplets in a group but gaseous conditions far from the cloud are specified and are not coupled with the droplet calculations. In the array theory, location of each droplet is specified as an initial condition and tracked in time. Fluid dynamics and transport, including flame structure, is carefully tracked throughout the continuous gaseous volume