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The interaction between internal heat gain and heat loss on compound-drop spray flames

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ABSTRACT

The effects of the shell-fuel mass fraction, the compound drop radius, and the liquid loading on one-dimensional laminar premixed flames are theoretically studied using large-activation-energy asymptotics. A compound drop is composed of a water core encased by a shell of *n*-octane. A completely prevaporized mode is identified, in which no liquid droplets exist downstream of the flame. The shell-fuel mass fraction dominates the internal heat transfer and vaporization rate for an individual compound drop, which may induce a positive effect (overall heat gain) or a negative effect (overall heat loss) on the flame. The liquid loading represents the total quantity of the compound-drop spray. The combined effects of the shell-fuel mass fraction and the liquid loading on the premixed flame show that the flame intensity is enhanced (suppressed) by overall internal heat gain (heat loss), i.e., the flame speed increases (decreases) due to the overall internal heat gain (heat loss). As a result, the residence time required for the drops to achieve prevaporization and the temperature profile of the pre-heating zone are significantly influenced by the flame speed. The critical values of the initial drop radius and the shell-fuel mass fraction that correspond to the critical condition of the completely prevaporized mode are determined by liquid loading and the flame propagation mass flux. The correlations among these factors are investigated.

1. Introduction

The spray combustion of liquid fuels is utilized in many energy applications, such as furnaces, diesel engines, gas turbines, and space rockets. Spray combustion is a complicated phenomenon as it involves many processes. A typical sequence of events is the injection and atomization of a liquid fuel, the mixing of droplets with oxidizing gas, heat transfer to droplets to produce evaporation, the mixing of fuel vapor with gas, gas-phase or liquid-phase ignition processes, and flame propagation. Spray combustion models can be classified as either homogeneous or heterogeneous [1], also referred to as locally homogeneous flow (LHF) and two-phase flow (TPF), respectively [2]. A homogeneous combustion flame is usually associated with the spray of volatile drops which have a small initial drop size, whereas a heterogeneous combustion flame contains drop diffusion flames.

A dilute oil spray can support a premixed flame that acts as an auxiliary fuel, enhancing flame intensity. Water spray or inert dust can be applied in combustion systems to quench fire, suppress flames, control flame temperature, or lower the local temperature. Recent developments in engines, industrial furnace design, and fuel formulation have made multi-component fuels important for efficiency improvement and emissions reduction. Examples of multi-component fuels are water–oil emulsion [3], ethanol–gasoline mixtures [4], and coal–water or coal–oil slurries [5]. For water–oil emulsion applications, the addition of water to oil may result in micro-explosions, which can improve combustion efficiency or lower the local temperature to subsequently reduce thermal NO emissions. However, the addition of water also induces a certain amount of heat loss. Combustion efficiency may deteriorate due to a large amount of heat loss if the water content in oil is excessively high. Therefore, the overall effects of water content on the flame of multi-component fuel should thus be studied.

A compound drop is a type of multi-component fuel. The constituent fluids are immiscible to each other. No surfactant is added to induce emulsion. In this study, a water-in-oil compound drop which contains a single core of water (surface tension greater than the shell fuel) encased by a layer of fuel is investigated. This type of compound drop has been generated using a piezoelectric generator with a concentric nozzle [6] or by colliding single-component drops [7]. Other types of compound drop have been created, such as methanol-in-alkane [8] or gas-in-oil compound drops [9].

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Nomenclature

Dimensional quantities

B'	frequency factor, m^3/mol s
c'_l	specific heat of liquid, kJ/kg K
c'_p	specific heat of gas, kJ/kg K
D'	mass diffusion coefficient, m^2/s
Ea'	activation energy, kJ/kg
G'	functions in Eqs. (1)–(4), G'_{1-3} : kg/m^3 s, G'_4 : kJ/m^{3}s
L'	latent heat of vaporization, kJ/kg
$\overline{M}'$	average molecular weight, kg/mol
$\dot{m}'_b$	droplet burning rate, kg/sK
$\dot{m}'_P$	flame propagation mass flux of a homogeneous mixture, kg/m^2 s
$\dot{m}'_v$	droplet vaporization rate, kg/s K
n'	number density of droplets, m^{-3}
P'	pressure, N/m^2
Q'	heat of combustion, kJ/kg
R'	universal gas constant, kJ/kg K
r'	droplet radius, m
r'_i	initial droplet radius, m
r'_w	initial core-water radius, m
T'	temperature, K
u'	flow speed, m/s
W'	burning rate at flame sheet, kg/m^3 s
x'	coordinate position, m
λ'	thermal conductivity coefficient, kJ/m s K
ρ'	density, kg/m^3

Non-dimensional quantities

A_F	parameter in Eq. (8)
A_W	parameter in Eq. (9)
L_i	latent heat of vaporization, L'_i/Q'
$\dot{m}$	flame propagation mass flux, $\dot{m}'/\dot{m}'_p$
$m_{v/b}$	mass vaporization/burning rate, $\dot{m}'_{v/b}c'_p/4\pi r'_i\lambda'$
T	temperature, $T'c'_P/Q'$
T_a	activation temperature, $E'_a c'_P/(Q'\widetilde{R}')$
T_∞	adiabatic flame temperature, $T'_\infty c'_P/Q'$
$T_{1,\infty}$	first-order temperature at downstream side of flame sheet for the completely prevaporized mode, representing the internal heat transfer of compound-drop spray
$T_1^+(0)$	first-order temperature at downstream side of flame sheet
x	transformed coordinate, $x'c'_p\dot{m}'_p/\lambda'$
Y	gaseous mass fraction, $Y_F = Y'_F$ and $Y_O = Y'_O/\sigma$
Z	gas-phase heterogeneity parameter, ρ'_g/ρ'

Greek symbols

α	$\alpha = 1$ and $\alpha = 0$ for lean and rich spray flames, respectively
γ	liquid loading, $Z_{-\infty} = 1 - \varepsilon\gamma$
ε	small expansion parameter, T_∞/T_a
ζ	$(1 - Z)/(1 - Z_{-\infty})$
ζ_w	core-water mass fraction, $1 - \omega$
Λ	flame speed eigenvalue
η	stretch variable of reaction zone, x/ε
σ	stoichiometric ratio
ϕ_g	equivalence ratio
ω	shell-fuel mass fraction

Subscripts

b	boiling state
c, s	critical completely prevaporized burning and shell prevaporized burning states, respectively
E	state at extinction
e	state at which droplet is completely vaporized
w	state at which shell fuel of droplet is completely vaporized
v	state at which shell fuel of droplet vaporization starts
out	outer region of flame
in	inner region of flame
F, O	fuel and oxygen, respectively
W	water
g, l	gas and liquid phases, respectively
i	i = F and O in lean and rich sprays, respectively
j	j = O and F in lean and rich sprays, respectively
0, 1	zeroth and first orders, respectively
$-\infty$	far upstream position and initial state
$+\infty$	far downstream position and final state

Superscripts

+, –	downstream and upstream sides of the flame outer zones, respectively
′	dimensional quantities

The characteristics of a liquid or solid spray in a laminar flame have been investigated theoretically by a number of researchers. Williams [10] discussed the considerations and derived the primary equations for dilute spray combustion. Heterogeneous flame characteristics for inert dust and spray were first investigated by Mitani [11]. Lin et al. [12] developed a theory for an off-stoichiometric dilute spray flame in which drop gasification follows the d^2-law of vaporization and combustion. A series of theoretical studies have been conducted on the effects of internal heat transfer [13], external heat transfer [14,15], flow stretch for a premixed flame [16], flow stretch by varying cross-sectional area [17], stretched spray flames with nonunity Lewis numbers in a stagnation-point flow [18], preferential diffusion [19], and their interactions [20]. In addition, Greenberg et al. [21] investigated the influences of the initial liquid loading and a poly-dispersed spray of droplets [22] for the heterogeneous mode of a laminar premixed flame. In contrast to the effect of fuel spray on flames, that of water spray [23,24] is suppression or even extinction. However, the above studies on spray combustion focused on single-component fuels or inert substances. Lin et al. [12] classified spray combustion into two modes according to the size of droplets, namely, the completely prevaporized burning (CPB) and the partially prevaporized burning (PPB) modes. In comparison with single-component drops, the situation for compound drops is more complex. In this study, the spray mode is split into the CPB, the shell prevaporized burning (SPB), and shell partially prevaporized burning (SPPB) modes according to the initial size of the compound drops and the shell-fuel mass fraction, i.e., the three modes are classified using the relative position of the flame with respect to the shell fuel and the core water gasification zones. The CPB mode is a limiting condition in which the droplets of the spray are small and volatile, becoming completely prevaporized before reaching the flame front. That is, the spray flame behaves as a homogeneous combustion flame.

The influences of flame-upstream and flame-downstream heat transfer on the flame intensity are different. The upstream heat gain or loss reaches the reaction zone by flow convective motion; therefore, it greatly affects flame intensity. In contrast, the effect of downstream heat transfer on the flame intensity by diffusion