Research Article

Analysis of Completely Prevaporized Spray Flames with Water/Octane Core/Shell Structured Droplets

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A series of studies on laminar flame propagation in off-stoichiometric dilute sprays of monodispersed inert or fuel drops had been investigated by large activation energy asymptotics. The present study extends previous theoretical model to consider water/octane core/shell structured drops instead of single-phase drops. The core/shell structured drops are composed of core fluid (water) encased by a layer of shell fluid (n-octane). In this study, we only deal with the case that core/shell structured drops are vaporized completely just at flame location. Namely, the discussions of this paper are restricted to the completely prevaporized mode. By varying parameters of core water radius, core-to-shell ratio, the amount of liquid loading, and the stoichiometric ratio (lean or rich burning), we examine the gasification of core water and shell fuel of core/shell structured drops upstream of the bulk flame and its relation to the internal heat transfer. The effects of drop radius, core-to-shell ratio, liquid loading, and overall heat loss or gain on flame propagation flux are reported and discussed.

1. Introduction

Motivation of the spray theory considering core/shell structured drops came from a providence notion of carrying certain purpose substance which is encased by a layer of shell liquid fuel into combustion system. For instance, core/shell structured drops are composed of core calcium oxide (CaO) suspension and shell diesel. As shell diesel burned out and produced carbon dioxide, the calcium oxide of core could capture CO₂ in situ of the combustion system. By varying core-to-shell ratio, the operation temperature and captured rate of CO₂ can be taken into account for an innovative combustion technology.

Owing to the successful introduction of large activation energy asymptotics in combustion, great progress has been made in understanding the physics of the flame [1–6]. As a result, numerous investigations have been devoted to asymptotic theories of steady deflagrations with heat losses [7–15], stretch [9, 11, 15–17], and preferential diffusion (nonunity Lewis number) [12, 13, 18].

In 1988, Lin et al. [19] had successfully introduced asymptotic techniques to analyze laminar flame propagation in off-stoichiometric dilute sprays. Subsequently, a series of theoretical researches were documented following the theoretical model. Huang et al. [20] investigated the influence of liquid loading on the flame propagation of dilute sprays in nonconserved systems. Those results indicated that the combustible spray in rich mixture plays a role as inert spray, leading to an S-shaped extinction curve similar to the result of Mitani [21]. It is well recognized that a homogeneous laminar premixed flame influenced by external heat loss can be adequately described by a C-shaped extinction curve (a double-valued function) [22] in which the extinction limit is identified by the turning point. The participation of fuel or inert spray effects further produced so-called internal heat transfer (heat gain or heat loss) to the system and thereby resulted in an S-shaped extinction curve (a triple-valued function) on spray flame extinction [22].

Water mist is an effective fire suppression agent, which is extensively used for fire protection/inhibition applications

[23–25]. Considering flow stretch and preferential diffusion, Liu et al. [26] had analyzed the influence of water sprays on the extinction of a methane-air premixed flame propagating in a stagnation point flow (a two-dimensional model) by using activation energy asymptotics. Subsequently, extinction characteristics of fuel-spray burning in the positively-stretched stagnation-point flow were investigated by Hou [27].

Extinction theory of spray premixed flames influenced by flame stretch and Lewis number can be modeled in a Bunsen flame tip. The effects of water and fuel spray on Bunsen flame tips were discussed in Lin et al.'s study [28]. Additionally, considering the propagation of a premixed flame in a closed tube with varying cross-sectional area [29], the flame can also be stretched due to the effects of nonuniform duct. It was concluded that positive flame stretch increases the mass burning rate for flames with Lewis number larger than unity, and negative flame stretch has the opposite effect.

Most practical liquid fuels are blends of many chemicals, and each is characterized by its own physical-chemical properties. The study reported by C. K. Law and H. K. Law [30] is of significant technical interest for multicomponent droplet combustion. The concept of core/shell structured drops which may be composed of core fluid (water, gases, or chemicals) encased by a layer of shell fluid (liquid fuel) has been recently introduced to the field of spray combustion by Chiu and Lin [31] in 2005. A stable stream of core/shell structured drops was produced by utilizing a piezoelectric drop generator equipped with concentric nozzles. The combustion and microexplosion of freely falling core/shell structured drops, generated by the collision of two single droplets, have been studied experimentally [32]. Microexplosion induced by internal superheating and hence nucleation was only observed for the collision-generated core/shell structured drops and is believed to be initiated by the air bubbles entrained during collision.

For the case of the core fluid being water and the shell fluid being fuel, it is expected that the internal heat transfer in the spray flame involves heat loss from water and heat gain from fuel for the lean burning, while it involves heat loss from both water and fuel for the rich burning. The core-to-shell (water-to-fuel) mass ratio plays an interesting role in results of overall heat loss or gain.

A completely prevaporized burning (CPB) mode ($r'_{-\infty} < r'_c$) and a partially prevaporized burning (PPB) mode ($r'_{-\infty} > r'_c$) are identified by a critical initial droplet size (r'_c) for the droplet to achieve complete vaporization at the premixed flame front. In this study, we consider water/octane core/shell structured drops under the completely prevaporized mode. By varying parameters of core water radius, core-to-shell ratio, the amount of liquid loading, and the stoichiometric ratio (lean or rich burning), we will examine the gasification of core/shell structured drops upstream of the bulk flame and its relation to the internal heat transfer. The effects of core water radius, core-to-shell ratio, liquid loading for lean and rich premixed flames on overall heat loss or gain, flame propagation mass flux, and critical radius will be discussed in detail in the following report.

FIGURE 1: Schematic diagram of completely prevaporized burning with core/shell structured drops spray. In this study, shell fuel vaporized in zone II; core water of core/shell structured drops vaporized in zone III and terminated at flame location ($x = 0$).

2. Theoretical Model

The concept of a core/shell structured drop is composed of core fluid (water) encased by a layer of shell fluid (liquid fuel), as shown in the dash frame of Figure 1. We adopt a one-dimension coordinated system in which a planar flame locates at $x = 0$, the two-phase combustible mixture composed of premixed fuel, air, and core/shell structured drops of a certain core-to-shell ratio comes from $x = -\infty$, and equilibrium reaction products moving away toward $x = +\infty$, as shown in Figure 1. The droplet motion is in phase with that of gas. The assumption of no slip is made for mathematical simplicity and physical clarity in understanding the phenomena of interest. In order to avoid the cold boundary difficulty related to droplet vaporization, we assumed that the liquid fuel starts to evaporate at $x = x_v$, only when the gas temperature has reached the boiling point of shell liquid of core/shell structured drops. At $x = x_w$, evaporation is complete for the layer of shell fluid, and in turn the core water starts to evaporate immediately. In the evaporation process, the droplets have a constant temperature and follow the d^2 -law. In this study, we only deal with the case that core/shell structured drops are vaporized completely just at flame location. Namely, the discussions of this paper are restricted to the completely prevaporized mode. As a result, the core/shell structured drop size is always equal to the critical radius (r'_c) and $x_e = 0$. The sections denoted by I, II, III, and IV are the upstream, shell fuel prevaporization, core water prevaporization, and downstream zones, respectively.

Since the spray is dilute, it is reasonable to assume that the amount of liquid loading is $O(\varepsilon)$ of the total spray mass in the asymptotic analysis. The small parameter of expansion ε is the ratio of thermal energy to activation energy in the combustion process ($\varepsilon = T_\infty/T_a$). Here we assume the small parameter of expansion in flame sheet inner analysis of reaction zone with the same order of ε , ($\varepsilon = x/\eta$). Moreover,

we assume that the fuel and oxidizer reaction for the bulk premixed flame is one-step overall, that microexplosion does not occur during the evaporation period of the shell fuel, and that those conventional constant properties simplifications apply. Finally, as soon as the shell fuel evaporated completely, the core water starts to evaporate immediately. The cross section area remains constant, and Lewis number is unity. More detailed assumptions and comments were generally described in the earlier study [19].

The total number of droplets crossing any plane normal to the x -axis per second is set to constant, $n'u' = n'_{-\infty}u'_{-\infty}$, and the overall continuity is given by $\rho'u' = \rho'_{-\infty}u'_{-\infty} = \dot{m}'$, where n' is the number density, ρ' is the overall density of the premixed and spray mixture, $\rho' = \rho'_G + \rho'_{S,F} + \rho'_{S,W}$, and $u'_{-\infty}$ represents the burning velocity of the mixture. The velocity of droplets is the same as that of the gaseous flow in all process. Note that $\rho'_{S,F} + \rho'_{S,W} = (4/3)\pi \cdot n'[(r'^3 - r_w'^3)\rho'_{L,F} + r_w'^3\rho'_{L,W}]$. In the analysis, quantities with and without primes are dimensional and nondimensional, respectively.

Based on the assumptions introduced above and following the previous formulations in [19, 33], the governing equations for overall continuity of gas-phase, conservations of fuel and oxidizer, and energy are given as follows.

Gas-phase continuity equation:

$$\frac{d}{dx'}(\rho'_G u') = G'_1. \quad (1)$$

Conservation equations of fuel and oxidizer:

$$\begin{aligned} \frac{d}{dx'} \left[\rho'_G u' Y'_F - (\rho'_G D')_F \frac{dY'_F}{dx'} \right] &= W' + G'_2, \\ \frac{d}{dx'} \left[\rho'_G u' Y'_O - (\rho'_G D')_O \frac{dY'_O}{dx'} \right] &= \sigma W' + G'_3. \end{aligned} \quad (2)$$

Energy equation:

$$\frac{d}{dx'} \left[\rho'_G u' C_p T' - \lambda' \frac{dT'}{dx'} \right] = -W' Q' + G'_4, \quad (3)$$

where W' is the function of burning rate at flame sheet:

$$W' = -\frac{B'}{M'_O} \left(\frac{P' \overline{M}'}{R'} \right)^2 Y'_F Y'_O \exp \left(-\frac{E'_a}{R' T'} \right) \quad (4)$$

and G'_1, G'_2, G'_3, G'_4 are the functions of evaporating rates, which are listed in Table 1.

However $\dot{m}'_v$ shows the evaporating rates for fuel or water; that is, $\dot{m}'_v = 4\pi r'(\lambda'/C_p p') \cdot \ln[1 + C_p'(T' - T'_b)/L']$, and L' denotes the latent heat of vaporization of fuel or water.

We also designate the extent of gas-phase heterogeneity by the parameter $Z = \rho'_G/\rho'$ [19, 33], so that $Z = 1$ represents the completely vaporized state. Then the nondimensional governing equations for the gas-phase continuity and conservations of fuel, oxidizer, and energy are, respectively, given by the following.

TABLE 1: The parameters shown in (1)–(3).

Evaporating zone	G'_1	G'_2	G'_3	G'_4
Zone II	$n' \dot{m}'_{v,F}$	$n' \dot{m}'_{v,F}$	0	$-n' \dot{m}'_{v,F} L'_F$
Zone III	$n' \dot{m}'_{v,W}$	0	0	$-n' \dot{m}'_{v,W} L'_W$

Gas-phase continuity equation:

For zone II,

$$\dot{m} \frac{dZ}{dx} = \frac{A_F}{T} (1 - Z_{-\infty})^{2/3} \cdot \left[\left(\frac{1 - Z}{1 - Z_{-\infty}} \right) - \frac{a}{b} \right]^{1/3} \cdot F(T, Y_O), \quad (5)$$

where

$$A_F = 3 \left(\frac{\lambda'}{\dot{m}'_p} \right)^2 \left(\frac{P' \overline{M}'}{R' C_p' Q' \rho'_{l,F}} \right) \left(\frac{1}{b} \right)^{2/3}, \quad (6)$$

$$a = \frac{\rho'_{l,W} - \rho'_{l,F}}{\rho'_{l,F}} r_w'^3, \quad (7)$$

$$b = r_{-\infty}'^3 + a \quad (8)$$

and the function

$$F(T, Y_O) = \ln \left[1 + \frac{(T - T_{b,F})}{L_F} \right]. \quad (9)$$

For zone III,

$$\dot{m} \frac{dZ}{dx} = \frac{A_W}{T} (1 - Z_w)^{2/3} (1 - Z)^{1/3} F(T, Y_O), \quad (10)$$

where

$$A_W = 3 \left(\frac{\lambda'}{r'_w \dot{m}'_p} \right)^2 \left(\frac{P' \overline{M}'}{R' C_p' Q' \rho'_{l,W}} \right) \quad (11)$$

and the function

$$F(T, Y_O) = \ln \left(1 + \frac{(T - T_{b,W})}{L_W} \right). \quad (12)$$

Conservation equations of fuel and oxidizer:

$$\begin{aligned} \frac{d}{dx} \left[Z \dot{m} Y_F - \frac{dY_F}{dx} \right] &= W + f_F \dot{m} \frac{dZ}{dx}, \\ \frac{d}{dx} \left[Z \dot{m} Y_O - \frac{dY_O}{dx} \right] &= W + f_O \dot{m} \frac{dZ}{dx}. \end{aligned} \quad (13)$$

Energy equation:

$$\frac{d}{dx} \left[Z \dot{m} T - \frac{dT}{dx} \right] = -W + f_T \dot{m} \frac{dZ}{dx}, \quad (14)$$

TABLE 2: The parameters used in (13) and (14).

Evaporating zone	f_F	f_O	f_T
Zone II	1	0	$-L_F$
Zone III	0	0	$-L_W$

where

$$W = - \left(\frac{B'\sigma}{M'_O} \right) \left(\frac{P'\overline{M}'}{R'} \right) \left(\frac{\lambda'}{Cp'\dot{m}_p'^2} \right) Y_F Y_O \exp \left(-\frac{Ta}{T} \right). \quad (15)$$

The parameters used in (13)-(14) are shown in Table 2. While $x = x'/l'_T$ is the dimensionless distance expressed in units of the preheating zone thickness, $l'_T = \lambda'/Cp'_G\dot{m}'_p$, $\dot{m}$ denotes the flame propagation mass flux normalized by the premixed value, $\dot{m}'_p$, in the homogeneous mixture ($\dot{m} = \dot{m}'/\dot{m}'_p$).

Performing the inner and outer expansions based on the small parameter of ε and following the detailed matching procedure of the previous study [19, 33] to match the inner and outer solutions, we therefore have the final results as follows:

$$\dot{m}^2 = \exp [T_1^+(0)]. \quad (16)$$

Equation (16) pointed out that the flame propagation flux is exponentially affected by the first-order downstream temperature near the flame. The first-order temperature is expressed by the following equation:

$$\begin{aligned} T_1^+(0) = \frac{\gamma}{T_\infty} & \left[\omega\alpha - \omega L_F - \omega(T_\infty - T_{b,F}) \right. \\ & - \omega \frac{Cp'_{L,F}}{Cp'_G} (T_{b,F} - T_\infty) \\ & - (1 - \omega) L_W - (1 - \omega)(T_\infty - T_{b,W}) \\ & \left. - (1 - \omega) \frac{Cp'_{L,W}}{Cp'_G} (T_{b,W} - T_\infty) \right]. \end{aligned} \quad (17)$$

For the sake of notation compactness, we use $\alpha = 1$ for lean sprays and $\alpha = 0$ for rich sprays. The liquid loading is represented by γ , through the expansion of $Z_\infty = 1 - \varepsilon\gamma$ for dilute sprays [19, 33]. For core/shell structured drops spray, we define a parameter, ω , which is the shell fuel mass fraction to initial core/shell structured drop. It is interesting to note that, in (17), two limiting cases, that is, pure fuel spray ($\omega = 1$) and pure water spray ($\omega = 0$), can be obtained, and the results are the same as formulated in our earlier studies [20, 22].

The first term on the right-hand side of (17) represents the effect of combustion heat from the shell fuel of liquid spray; the second and fifth terms show the effects of the latent heat coming from fuel and water; the third and sixth terms designate the effect of gaseous sensible heat; and the fourth and the last term show the effect of the liquid sensible heat of spray liquid loading.

TABLE 3: Physical properties of n-octane and water.

Physical property	n-Octane (C_8H_{18})	Water (H_2O)
Specific heat of liquid, Cp'_l (kJ/kg-K)	2.23	4.18
Latent heat of vaporization, L' (kJ/kg)	299.7	2253.9
Heat of combustion, Q' (kJ/kg)	44726	0
Density, ρ'_l (kg/m ³)	692	1000
Boiling temperature, T'_b (K)	398.6	373.0

3. Results and Discussion

The zeroth-order solutions of (13)-(14) are quite like the resolutions of analysis for homogeneous gas-phase mixture flame. The influence of liquid loading on flame behavior is designated by the solutions of the first-order terms. Flame propagation flux ($\dot{m}$) corresponds to the flame intensity. A spray flame with $\dot{m} > 1$ represents that flame intensity is strengthened by the spray with water/octane core/shell structured drops. Conversely, A spray flame with $\dot{m} < 1$ indicates that the spray has a negative effect on flame intensity.

Sample calculations based on (16) and (17) for water/octane core/shell structured drops under the completely prevaporized mode are considered in a nonconserved manner which maintains the initial gas-phase composition but varies the liquid loading. The core/shell structured drop comprises a water core and an octane (C_8H_{18}) shell. Table 3 lists the physical properties of n-octane and water used in our calculations. Thus, the influence of core/shell structured drops spray will be independently explored without the participation of the leaning effect from the gas-phase mixture. By varying parameters of core water radius (r'_w), shell fuel ratio (ω), the amount of liquid loading (γ), and the stoichiometric ratio (lean or rich burning), we will examine the gasification of water/octane core/shell structured drops upstream of the bulk flame and its relation to the internal heat transfer.

3.1. Effect of Core/Shell Structured Drops on Lean Spray Flames.

The core water and shell fuel of core/shell structured drops absorb heat in zones II and III for upstream prevaporization, resulting in internal heat loss. For a lean spray, the shell liquid fuel absorbs heat for gasification, produces the secondary gasified fuel for the bulk gas-phase burning, and enhances the burning intensity of the spray flame. Here, the secondary gasified fuel is defined as the amount of shell liquid fuel vaporized before reaching the flame. However, contrary to the shell liquid fuel, the core water absorbs heat for upstream vaporization, producing the gasified water (vapor) which is equivalent to an inert substance without any contribution to burning, thus providing an overall internal heat loss and subsequently weakening the flame. Therefore, for the case of the core fluid being water and the shell fluid being fuel, it is apparent that the overall internal heat transfer in the spray flame involves heat loss from water and heat gain from fuel for the lean burning, while it involves heat loss from both water and fuel for the rich burning.

FIGURE 2: Shell fuel mass ratio (ω) and critical radius (r'_c) of core/shell structured drops as a function of liquid loading (γ) with various core water radius (r'_w) for a lean octane/water core/shell structured drop spray flame.

Figure 2 shows the variations of critical radius (r'_c) and shell fuel ratio (ω) of core/shell structured drops with the spray liquid loading (γ). For a fixed radius of inner core water (r'_w), both the critical radius (r'_c) and shell fuel ratio (ω) of core/shell structured drops decrease when the liquid loading (γ) is increased. In this study, we only consider the completely prevaporized burning (CPB) mode and $r'_{-\infty} = r'_c$. The remarkable decrease of the critical radius at low liquid loading is expected to be caused by the dramatically increased shell fuel ratio for a lean flame.

As illustrated in Figure 3, for a lean flame ($\Phi_G = 0.8$) with a fixed liquid loading $\gamma = 0.02$, the critical radius (r'_c) increases with shell fuel ratio (ω) because the evaporating rate of octane is greater than water. The x_v , x_w , and x_e lines show the positions that shell fuel starts to evaporate, core water starts to evaporate, and droplet is completely vaporized, respectively. The corresponding regions of II and III can refer to Figure 1. The values of x_w are affected by shell fuel ratio and critical radius simultaneously.

The results indicated in Figure 4 show that the flame flux and internal heat transfer for a lean flame with $\gamma = 0.02$ are increased with shell fuel ratio. The spray effect can be positive or negative, depending on the shell fuel ratio of core/shell structured drops. For octane/water core/shell structured drops, as $\omega = 0.09805$, the positive effect and negative effect are equal; that is, overall heat transfer $Q_T = 0$. The positive effect of core/shell structured drop spray

FIGURE 3: Variations of gasification positions of shell fuel (x_v), core water (x_w , x_e), and critical radius (r'_c) with shell fuel ratio (ω) for a lean octane/water core/shell structured drop spray flame.

FIGURE 4: Flame flux ($\dot{m}$) and overall internal heat transfer (heat gain or loss), Q_T , as a function of shell fuel ratio (ω) for a lean octane/water core/shell structured drop spray flame.

corresponds to $\dot{m} > 1$ and $Q_T > 0$. In other words, the burning intensity of the flame is enhanced due to the overall internal heat gain as $\omega > 0.09805$.

3.2. Effect of Core/Shell Structured Drops on Rich Spray Flames. Contrary to a lean flame, for a rich flame, shell fuel of core/shell structured drops cannot provide extra combustion heat. This is because there is no oxygen for the gasified shell fuel to combust in a rich spray flame according to the assumption that the fuel and oxidizer reaction for the bulk premixed flame is one-step overall. Accordingly, the gasified

FIGURE 5: Shell fuel mass ratio (ω) and critical radius (r'_c) of core/shell structured drops as functions of liquid loading (γ) with various core water radius (r'_w) for a rich octane/water core/shell structured drop spray flame.

shell fuel makes no contribution to burning. Therefore, the overall internal heat transfer of spray is always overall internal heat loss.

The variations of critical radius (r'_c) and shell fuel ratio (ω) of core/shell structured drops with the spray liquid loading (γ) are demonstrated in Figure 5. For a fixed core water radius (r'_w), with increasing liquid loading (γ), the critical radius (r'_c) and shell fuel ratio (ω) of core/shell structured drops are increased, as illustrated in Figure 5. For the reason that the shell fuel cannot provide extra combustion heat for a rich flame, the variation of critical radius is only affected by the latent and sensible heat of core/shell structured drops. Comparing with the results shown in Figure 2, the variations of critical radius with liquid loading in Figure 5 show the opposite trend.

For a rich flame of $\Phi_G = 1.5$ with a fixed liquid spray loading of $\gamma = 0.02$, with increasing the shell fuel ratio (ω), the critical radius is increased because of the greater evaporating rate of octane as compared with water, as shown in Figure 6.

The results illustrated in Figure 7 show that the flame flux ($\dot{m}$) and internal heat transfer (Q_T) are increased with increasing shell fuel ratio. For a rich flame, the spray effect is always negative. This is caused by the overall internal heat losses, which consist of the coupling effects of the latent and sensible heat coming from shell fuel and core water. The negative effect of the spray implies that the burning intensity

FIGURE 6: Variations of gasification positions of shell fuel (x_v), core water (x_w , x_e), and critical radius (r'_c) with shell fuel ratio (ω) for a rich water/octane core/shell drop spray flame.

FIGURE 7: Flame flux ($\dot{m}$) and internal heat gain (or loss), Q_T , as a function of shell fuel ratio (ω) for a rich octane/water core/shell structured drops spray flame.

of the rich flame is weakened due to the overall internal heat loss; that is, $\dot{m} < 1$ and $Q_T < 0$.

4. Conclusions

A theory of core/shell structured drops spray flame was further developed using large activation energy asymptotics to explore the influence of liquid loading (γ) and shell fuel mass ratio (ω) of core/shell structured drops spray on the internal heat transfer (Q_T), flame mass flux ($\dot{m}$), and

critical radius (r'_c). The concluding remarks are summarized as follows.

For a lean spray, the shell liquid fuel absorbs heat for gasification, produces the secondary gasified fuel for the bulk gas-phase burning, and enhances the burning intensity of the spray flame. However, contrary to the shell liquid fuel, the core water absorbs heat for upstream vaporization, producing the gasified water (vapor) which is equivalent to an inert substance without any contribution to burning, thus providing an overall internal heat loss and subsequently weakening the burning intensity.

For a lean flame, core/shell structured drops spray can cause heat gain or heat loss, depending on shell fuel ratio. For the case of octane/water core/shell structured drops, as $\omega = 0.09805$, the positive effect and negative effect are equal. Hence, the burning intensity of the flame is enhanced due to the overall internal heat gain as $\omega > 0.09805$.

Contrary to a lean flame, for a rich flame, shell fuel of core/shell structured drops cannot provide extra combustion heat because the gasified fuel of shell fuel is equivalent to an inert substance without any contribution to burning. Consequently, the overall internal heat transfer of spray is always overall internal heat loss. The negative effect of the spray implies that the burning intensity of the rich flame is weakened due to the overall internal heat loss. Additionally, the latent heat of water is greater than octane; therefore, the heat loss is increased with decreasing shell fuel ratio.

Nomenclature

Dimensional Quantities

B' : Preexponential factor
 Cp' : Specific heat at constant pressure
 D' : Mass diffusion coefficient
 G' : Functions of Table 1
 L' : Latent heat of vaporization
 l'_T : Thickness of the diffusion zone, $\lambda' / \dot{m}'_p Cp'$
 M' : Molar mass of species
 $\dot{m}'$: Mass flow rate, $\rho' u' = \rho'_{-\infty} u'_{-\infty} = \dot{m}'$
 $\dot{m}'_v$: Evaporation rate
 $\dot{m}'_p$: Mass flow rate of pure premixed gas
 n' : Number density
 P' : Pressure
 Q' : Heat of combustion per unit mass of fuel
 R' : Universal gas constant
 r' : Droplet radius
 r'_c : Critical radius
 r'_w : Initial core water radius of core/shell structured drop
 $r'_{-\infty}$: Initial droplet radius
 u' : Axial flow velocity
 T' : Temperature
 T'_a : Activation energy temperature
 W' : Combustion rate defined by (4)
 x' : Axial distance
 Y' : Mass fraction of species.

Nondimensional Quantities

A_F : Parameter defined by (5)
 A_W : Parameter defined by (10)
 f : Parameter defined in Table 2
 L : Latent heat of vaporization, $L = L' / Q'$
 $\dot{m}$: Mass flux, $\dot{m} = \dot{m}' / \dot{m}'_p$
 T : Temperature, $T = T' Cp' / Q'$
 T_{∞} : Adiabatic flame temperature
 W : Parameter defined by (15)
 x : Axial coordinates, $x = x' / l'_T$
 Y : Mass fraction, $Y_F = Y'_F$, $Y_O = Y'_O / \sigma$
 Z : Gas-phase heterogeneity, $Z = \rho'_G / \rho'$.

Greek Symbols

α : Condition parameter of (17), $\alpha = 1$ for lean and $\alpha = 0$ for rich condition
 ε : Small expansion parameter
 γ : Spray liquid loading
 η : Thickness of flame sheet
 λ' : Thermal conductivity
 ρ' : Density of overall
 ρ'_G : Gas-phase density
 $\rho'_{S,F}$: Density of liquid fuel
 $\rho'_{S,W}$: Density of liquid water
 σ : Stoichiometric ratio
 ω : Shell fuel mass ratio of core/shell structured drop
 Φ_G : Equivalence ratio.

Subscripts

b : Boiling state
 e : State of droplet is completely vaporized
 F, O, W : Fuel, oxygen, and water
 G, L : Gas and liquid phases
 v : State of shell fuel evaporation initiates
 w : State of core water evaporation initiates
 $0, 1$: Zeroth- and first-order symbols
 $-\infty, \infty$: Initial and final states.

Superscripts

$+$: Downstream of the flame symbol
 t : Dimensional quantities symbol.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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