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INFLUENCE OF WATER SPRAYS AND HEAT LOSS ON PROPANE/AIR FLAMES PROPAGATING IN A STAGNATION-POINT FLOW

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ABSTRACT The objective of this study is to investigate the extinction characteristics of propane/air flames under the influences of Lewis number, flow stretch, internal heat loss and external heat loss using activation energy asymptotics. We consider a steady, planar, premixed flame generated in a stagnation-point, two-phase flow in which the dispersed phase is simulated by a monodisperse, dilute and chemically inert spray (water spray). A completely prevaporized mode and a partially prevaporized mode of flame propagation are identified by a critical initial droplet size (r_c') for the droplet to achieve complete evaporation at the premixed flame front. Internal heat loss associated with water vaporization increases with increasing liquid loading or decreasing initial droplet size. The (positive) flow stretch coupled with Lewis number (Le), respectively, weakens and intensifies the burning intensity of the lean propane/air flame (Le>1) and rich propane/air flame (Le<1). Additionally, the external heat loss (K) weakens the burning intensity and has a significant influence on the flame behavior. The results show that the Le>1 flame can be extinguished with or without external heat loss. Flame extinction characterized by a C-shaped curve is dominated by the external heat loss or the flow stretch. For the Le<1 flame without external heat loss, no extinction occurs under the influence of flow stretch. However, the Le<1 flame with completely prevaporized water sprays enduring a small amount of flow stretch can be extinguished by the external heat loss and this behavior is characterized by a C-shaped curve. Note that the W-shaped extinction curve is mainly governed by the internal heat loss. Flame extinction characterized by a W-shaped curve occurs when the Le<1 flame with external heat loss endures a positive stretch and experiences a partially prevaporized water spray having sufficiently large liquid loading and droplet size.

Keywords: Flame Extinction, Dilute Spray, Lewis Number, Stretch, Stagnation-Point flow, Heat Loss

1. INTRODUCTION

Extinction of a steadily burning flame can be achieved by external heat loss [1-3] and flow stretch [4-7] separately. A homogeneous laminar premixed flame influenced by external heat loss can be adequately described by a C-shaped extinction curve (a double-valued function) [1-3] in which the extinction limit is identified by the turning point. Furthermore, the burning intensity of the positively-stretched flame in a stagnation-point flow is weakened or strengthened depending on the mixture Lewis number is greater or smaller than one, respectively [4-7]. Here the Lewis number is identified as the ratio of thermal-to-mass diffusivities of the deficient reactant in the mixture. Regardless of incomplete reaction and downstream heat loss through the wall, a Le>1 flame can be extinguished by a sufficiently large stretch, while no extinction occurs for a Le<1 flame. Note that flame extinction influenced by stretch is also characterized by a C-shaped extinction curve.

Besides external heat loss [1-3] and flow stretch [4-7], the application of inert spray [8] or chemical reactive effects [9] produced so-called virtual (or internal) heat loss, which is associated with the gasification process of the dispersed phase, and thus led to the S-shaped extinction curve (a triple-valued function) in distinction from the C-shaped extinction one described above. The extinction of a dilute spray flame suffering external heat transfer designated by the bulk heat conduction from the system to the surrounding has been extensively analyzed in one-dimensional models [10-12]. It was found that the trend of flame extinction is mainly governed by the external heat loss and is only slightly modified by the internal heat loss associated with the spray effect. In those theoretical studies [10-12], however, the coupled effects of flow stretch and preferential diffusion on the flame extinction of dilute sprays were not examined.

An extinction theory of stretched premixed flames propagating in a stagnation-point flow by inert sprays using activation energy asympotics was first reported by Liu and Lin [13]. It was concluded that owing to the participation of the inert spray, extinction characterized by an S-shaped curve is possible for the Le < 1 flame. Conversely, the Le > 1 flame strongly influenced by flow stretch can be extinguished with or without the participation of the inert spray. Unfortunately, this study did not include the interaction between internal heat loss and external heat loss on positively-stretched premixed flames with nonunity Lewis number, which is of great significance but has not yet been examined.

The objective of this study focuses on the extinction characteristics of the propane/air flame propagating in a stagnation-point flow under the influences of Lewis number, flow stretch, internal heat loss and external heat loss. We consider a steady, planar, premixed flame generated in a stagnation-point, two-phase flow in which the dispersed phase is simulated by a monodisperse, dilute and chemical inert spray. The heat transfer mechanism is composed of the internal heat loss and the external heat loss. Here the internal heat loss associated with droplet gasification is a function of liquid water loading and liquid water droplet size. The external heat loss is assumed to exist in the upstream region of the premixed flame. The analysis is

restricted to dilute sprays, so that the amount of liquid water loading in the fresh mixture is very small and can be expanded in perturbation analysis.

2. THEORETICAL MODEL

The stagnation-point flow considered here is generated by impinging a two-phase premixture of gaseous fuel, air and liquid water droplets onto a wall which is adiabatic and impermeable, as shown in Fig. 1. The injection velocity at the burner exit is assumed to be uniform and is denoted by a nondimensional value, U. The cylindrical coordinates (x, y) with the origin at the center of the wall are nondimensionalized by the separation distance (L') between the burner and the wall. The locations of the burner exit and the premixed flame are, respectively, denoted by 1 and x_f. By defining a critical initial droplet size (r_c') for a droplet to achieve complete evaporation at the premixed flame front, we have completely prevaporized and partially prevaporized sprays as $r_i' \le r_c'$ and $r_i' > r_c'$, respectively [9-12]. We assume that the droplet will start to evaporate only when the gas temperature has reached the boiling point of the liquid. Droplets then vaporize upon crossing the flame, and will vanish at $x=x_e$ upon complete evaporation.

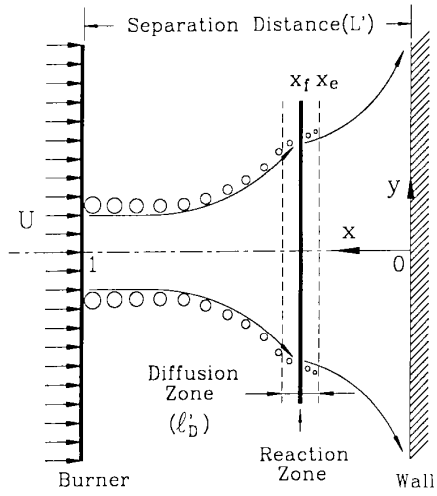

Fig. 1. Schematic diagram of a premixed flame propagating a stagnation-point flow under the influence of water sprays.

On the basis of large activation energy asymptotics, we simply assume that a small parameter $\delta = \ell_D' / L' << 1$, where $\ell_D' = \lambda' / (\rho_{Gi}' C_{PG}' S_L^0)$ indicates the thickness of the diffusion zone; here λ' is the thermal conductivity, C_{PG}' is the specific heat at constant pressure, ρ_{Gi}' is the density of fresh gas at the burner exit and S_L^0 is the one-dimensional adiabatic laminar flame speed of a premixed flame. According to the fast chemical reaction, a thinner reaction zone is further assumed to be embedded within the diffusion zone, as shown in Fig. 1. Since the spray is dilute and monodisperse, it is reasonable to assume that the amount of liquid loading is O(ε) of the total mixture mass. Here the small parameter of expansion, ε, is the ratio of thermal energy to large activation energy in the combustion process. In the analysis, small parameters δ and ε are assumed to be of the same order for the matching of the reaction zone [11]. Furthermore, we consider moderate rates of flow stretch allowing the flame to sit outside the viscous boundary layer. Finally, we assume that the fuel and oxidizer reaction for the bulk premixed flame is one-step overall, that the droplet gasification follows the d^2-law, and that constant property simplifications apply. More detailed assumptions and comments were generally described in earlier studies [11, 12].

We designate the extent of gas-phase heterogeneity by the variable $z=\rho_G'/\rho'$, in which ρ' is the overall density of the two-phase mixture, such that z=1 represents the completely vaporized state. Therefore, the nondimensional equations for gas-phase continuity, conservations of fuel, oxidizer, energy and momentum are given by, respectively,

$$\frac{\partial}{\partial x}(\rho z u) + \frac{1}{y}\frac{\partial}{\partial y}(y\rho z v) = \delta^{-1}\bar{A}\,(1-z)^{1/3}(1-z_i)^{2/3}\ln\left[1+\left(T-T_b\right)/h_{LG}\right], \tag{1}$$

$$\frac{\partial}{\partial x}(\rho z u Y_j) + \frac{1}{y}\frac{\partial}{\partial y}(y\rho z v Y_j) - \delta\,Le_j^{-1}\left[\frac{\partial^2 Y_j}{\partial x^2} + \frac{1}{y}\frac{\partial}{\partial y}\left(y\frac{\partial Y_j}{\partial y}\right)\right] = \delta^{-1}W,\ j = F, O \tag{2}$$

$$\frac{\partial}{\partial x}(\rho z u T) + \frac{1}{y}\frac{\partial}{\partial y}(y\rho z v T) - \delta\left[\frac{\partial^2 T}{\partial x^2} + \frac{1}{y}\frac{\partial}{\partial y}\left(y\frac{\partial T}{\partial y}\right)\right] = -\delta^{-1}WQ - h_{LG}\left[\frac{\partial}{\partial x}(\rho z u) + \frac{1}{y}\frac{\partial}{\partial y}(y\rho z v)\right] - \delta K(T-T_i)H(x), \tag{3}$$

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\bar{P}\frac{\partial P}{\partial x} + \delta\,\mathrm{Pr}\left[\frac{\partial^2 u}{\partial x^2} + \frac{1}{y}\frac{\partial}{\partial y}\left(y\frac{\partial u}{\partial y}\right)\right], \tag{4}$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\bar{P}\frac{\partial P}{\partial y} + \delta\,\mathrm{Pr}\left[\frac{\partial^2 v}{\partial x^2} + \frac{\partial}{\partial y}\left(\frac{1}{y}\frac{\partial}{\partial y}(yv)\right)\right], \tag{5}$$

where

$$\bar{P} = P_i'/\rho_i'(S_L^0)^2, \tag{6}$$

$$\bar{A} = 3\,\ell_D'^2\,P'\bar{\tilde{M}}/[T_i'\rho_L'\tilde{R}(r_i')^2], \tag{7}$$

$$W = -(B'\sigma/\bar{\tilde{M}}_O)(P'\bar{\tilde{M}}'/\tilde{R})^2\left\{\lambda'/C_{PG}'[\rho' S_L^0]^2\right\}Y_F Y_O \exp(-T_a/T) \tag{8}$$

and the function

$$H(x) = \begin{cases} 1 & \text{for } x_f \le x \le x_v, \\ 0 & \text{for } x < x_f \text{ or } x > x_v. \end{cases} \tag{9}$$

In the above equations, $Q=Q'/\left(C_{PG}'T_i'\right)$ and $h_{LG}=h_{LG}'/\left(C_{PG}'T_i'\right)$ represent the heat of combustion per unit mass of gaseous fuel and the latent heat of vaporization for the liquid water, respectively. Quantities with and without primes are dimensional and nondimensional, respectively. Furthermore, the ideal gas equation and the conservation of mass flux for the axisymmetric stream tube are applied to the derivation of the gas-phase continuity.

Performing the separate analysis on three regions, namely the diffusion zone, the reaction zone and the outer hydrodynamic zone, and following the detailed matching procedure of ref. [11], we have the final results as follows:

$$\dot{m}_0^2 = \exp[T_1(0^+)/T_{ad}]\,. \tag{10}$$

The first-order temperature $T_1(0^+)$ is expressed as

$$T_1(0^+) = \gamma\bar{D} - \frac{\bar{K}\Gamma}{\dot{m}_0^2} - \frac{K}{\dot{m}_0^2}\{1 - \ln[(T_b - T_i)/(T_f - T_i)]\}QY_{ji} \tag{11}$$

where $\Gamma = QY_{ji}\int_0^1 [1-\tilde{\omega}^{(Le_j-1)}]/(1+\tilde{\omega}QY_{ji})d\tilde{\omega}$ represents the Lewis number effect, and $\bar{K} = \frac{1}{y}\frac{\partial}{\partial y}(yv)$ shows the flow stretch. The spray effect comes from $\gamma\bar{D}$ in Eq. (11), where

$$\bar{D} = [T_b - \frac{C'_{PL}}{C'_{PG}}(T_b - 1)] - (T_{ad} + h_{LG})(1 - \dot{m}_0\int_0^{\xi_e} z_0 e^{-\dot{m}_0\xi}d\xi) \tag{12}$$

and

$$\xi_e = z_0(0)^{2/3}/\{2\bar{A}\ln[1+(T_{ad}-T_b)/h_{LG}]/(3\dot{m}_0 T_{ad})\} \tag{13}$$

showing the completely vaporized state. In addition, K is a heat transfer coefficient, which denotes the effect of upstream external heat loss. A larger value of K means that the premixed flame with dilute water spray suffers a larger amount of external heat loss. The liquid water loading is represented by γ through the expansion of $z_i = 1 - \delta\gamma$ [12]. For completely prevaporized sprays, Eq. (9) is simplified to be

$$\bar{D} = [T_b - \frac{C'_{PL}}{C'_{PG}}(T_b - 1)] - (T_{ad} + h_{LG})\,, \tag{14}$$

indicating that there is no contribution on $T_1(0^+)$ coming from the droplet size.

3. RESULTS AND DISCUSSION

Sample calculations based on Eqs. (10) and (11) for propane burning in air are now considered. In addition to two parameters of r_i' and γ showing the internal heat loss for the water spray, we also consider flow stretch ($\bar{K}$), Lewis number (Le) and external heat loss (K) in the problem. Since there is a linear relation between U and $\bar{K}$ [11], we use U instead of $\bar{K}$ as a measurable variable to represent flow stretch. Lewis number is defined as $\lambda'/\rho'_G C'_{PG} D'_j$ in which the diffusion coefficient of the deficient reactant in the mixture is used. Results of lean propane flames with Le>1 and rich propane flames with Le<1 are separately discussed in the following sections.

3.1 Lean Flames with Water Sprays

Figure 2 shows flame propagation flux ($\dot{m}_0$) and flame position (x_f) as a function of the flow stretch (U) for the lean propane/air flames with completely prevaporized sprays ($r_i' \le r_c'$) under the influence of external heat loss (K). Since the planar flame in divergent stagnation-point flow suffers positive stretch, an increase in flow stretch will result in the decrease of burning intensity for Le>1 flame. Accordingly, the upper and lower branches of the C-shaped extinction curves, respectively, represent the stable and unstable solutions. The extinction limit, identified by the turning point in connecting the upper and lower branches, demonstrates that flame extinction occurs if the flow stretch is large enough. For the case of K=0, both earlier studies and present work show that in the absence of the external heat loss, the Le>1 flame is pushed closer to the stagnation plane and has a smaller $\dot{m}_0$ with increasing flow stretch. Hence, a sufficiently large flow stretch leads to flame quenching. This indicates that the Le>1 flame can be extinguished by the flow stretch alone. Introducing the $O(\delta)$ amount of external heat loss to the system, the value of U at extinction decreases with the increase of K, as shown in Fig.2, since increasing K will diminish the burning intensity of the lean flame with Le>1.

Figure 3 shows the flame propagation flux ($\dot{m}_0$) and the flame position (x_f) of the lean propane/air flame as a function of the external heat loss (K) and the liquid loading (γ) for a given flow stretch (U=1.1) under completely prevaporized water sprays. Starting with the characteristic curve of γ =0 referred to the burning conditions of a

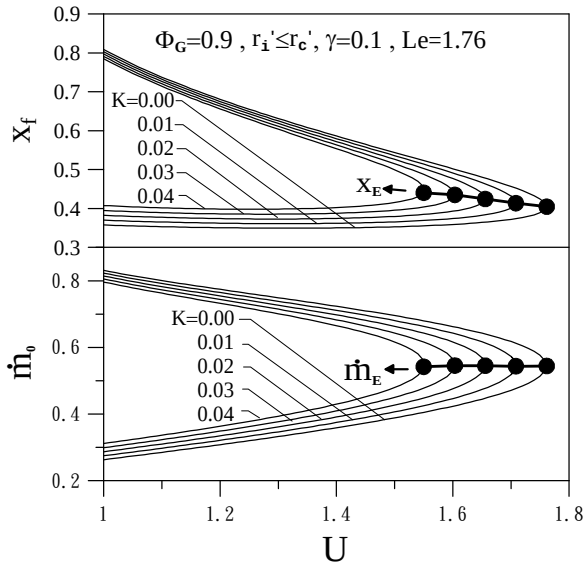

Fig. 2. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with the flow stretch (U) and the external heat loss (K) for lean propane/air flames under completely prevaporized water sprays.

homogeneous premixture experiencing the external heat loss, results show that with increased liquid loading, the $\dot{m}_0$ curve shifts downward. Considering the droplet gasification processes for a lean flame, the liquid water absorbs heat for upstream vaporization, producing the gasified water (vapor) which is equivalent to an inert substance without any contri-

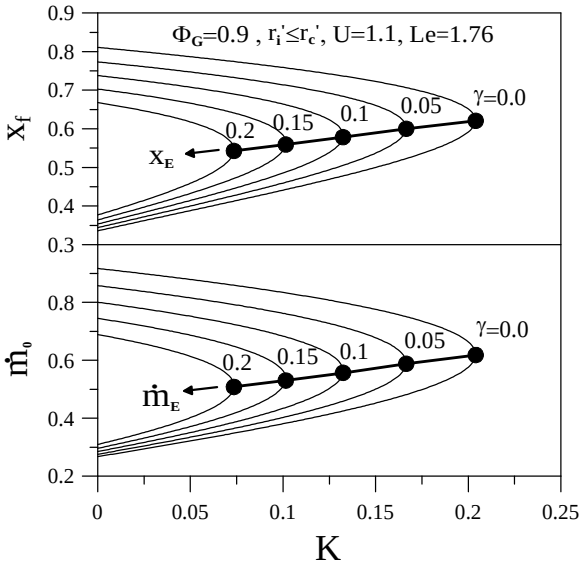

Fig. 3. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with liquid loading (γ) and the external loss (K) for lean propane/air flames at U=1.1 under completely prevaporized water-spray conditions.

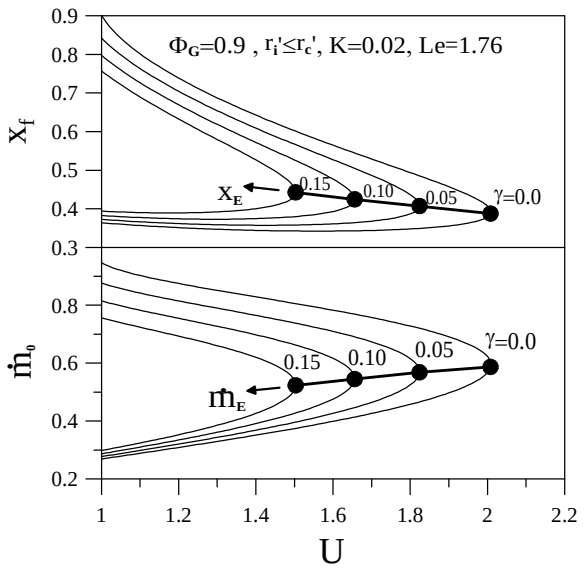

Fig. 4. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with the flow stretch (U) and the liquid loading (γ) for the lean propane/air flame at K=0.02 under completely prevaporized water sprays.

bution to burning, thus providing an overall internal heat loss, and subsequently weakening the flame propagation flux. Hence, the amount of external heat loss required for flame extinction of a lean flame with water sprays is lower than that required for a homogeneous premixture. Additionally, The critical values of $\dot{m}_0$ at extinction, $\dot{m}_E$, for the lean flames with water sprays decreases with increasing γ.

Figure 4 shows the flame propagation flux ($\dot{m}_0$) and the flame position (x_f) of the lean propane/air flame as a function of U and γ for K=0.02 under completely prevaporized water sprays ($r_i' \le r_c'$). Since stretch is positive in stagnation- point flow, an increase in flow stretch leads

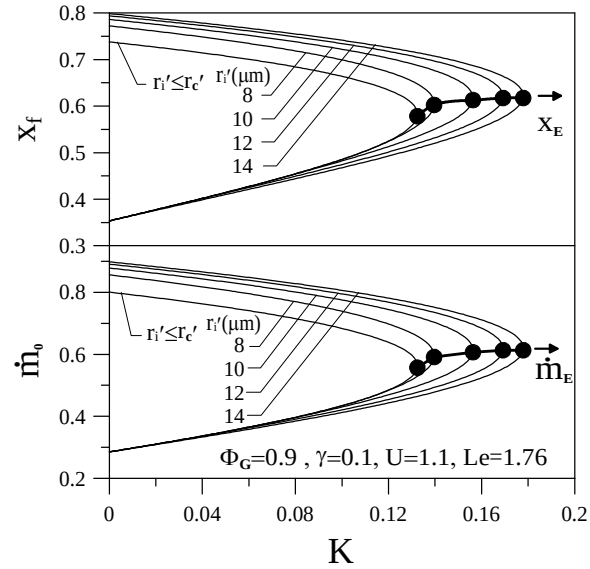

Fig. 5. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with the external heat loss (K) and the droplet size (r_i') for a lean propane/air flame under partially prevaporized water sprays.

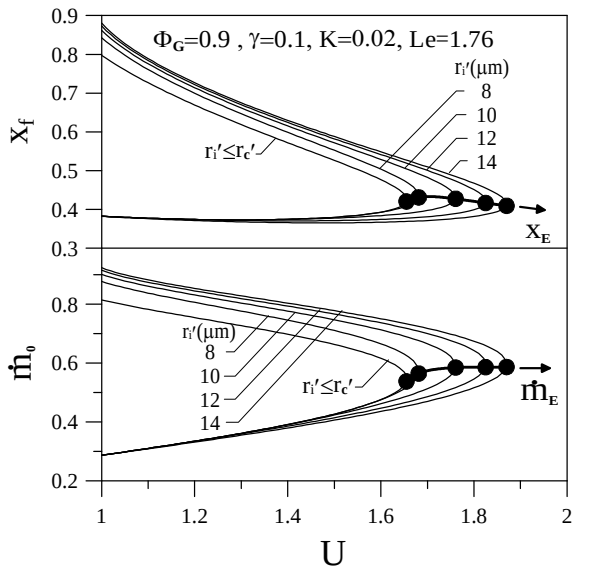

Fig. 6. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with the flow stretch and the droplet size (r_i') for a lean propane/air flame under partially prevaporized water sprays.

to the decrease of burning intensity for Le>1 flame. For a given γ, the increase of U first results in decreases of both $\dot{m}_0$ and x_f indicating that a weakened flame sits closer to the stagnation plane experiencing a larger flow stretch, and finally leads to flame extinction when the flow stretch is sufficiently large. This phenomenon is mainly owing to the suppression of burning intensity by flow stretch for a Le>1 flame. For a given K, the lean flame with a larger γ, providing additional internal heat loss through the droplet vaporization, will be extinguished at a smaller flow stretch, as shown in Fig. 4. Since both flow stretch and external heat loss have negative effects on the Le>1 flame, it is clear that extinction of a lean flame with Le>1 is mainly dominated by the flow stretch or the external heat loss, and

is slightly modified by the internal heat loss resulted from water droplets vaporization.

Concerning the partially prevaporized water sprays ($r_i' > r_c'$), the influence of the initial droplet size on flame characteristics is shown in Fig. 5 for the lean propane/air flame of Φ_G=0.9, γ=0.1, U=1.1 and Le = 1.76. Figure 5 depicts that for a given flow stretch (U=1.1), with increasing initial droplet size, the upper branch of the C-shape extinction curve corresponding to the stable solution for a partially prevaporized spray gradually deviates from that for the completely prevaporized spray ($r_i' \le r_c'$). This finding illustrates that the flame propagation flux increases with increased initial droplet size due to the decrease of internal heat loss. Considering the droplet gasification process for a water spray, the liquid droplet absorbs heat for upstream vaporization and eventually leads to internal heat loss. A lean flame containing larger droplets experiences a weaker upstream prevaporization, provides a smaller amount of internal heat loss, and thereby has a larger burning intensity. Hence, it can be extinguished by a larger external heat loss.

The effect of the initial droplet size on flame extinction for a lean propane/air flame of Φ_G=0.9, γ=0.1, K=0.02, and Le = 1.76 is shown in Fig. 6. The C-shaped extinction curves, dominated by flow stretch, are also seen in Fig. 6. It is expected that increasing r_i' suppresses the droplet vaporization resulting in a smaller heat loss and that increasing flow stretch (U) reduces the burning intensity of the positively-stretched flame with Le>1. Therefore, the value of U at extinction decreases with increasing r_i'. Moreover, it is found that the $\dot{m}_E$ value increases with increasing r_i'.

3.2 Rich Flames with Water Sprays

For a given γ=0.05, Fig 7 shows that with increasing flow stretch, the Le < 1 flame without external heat loss (K=0.0) is pushed closer to the wall (corresponding to a smaller x_f) and has a larger flame propagating flux ($\dot{m}_0$). Note that no extinction occurs under the influence of flow stretch for the rich propane/air (Le < 1) with completely prevaporized water sprays but without external heat loss. However, the flow stretch still dominates the flame characteristics. Introducing the O(δ) amount of external heat loss to the system, extinction does exist for rich propane/air flame if the external heat loss is large enough. Since increasing K will diminish the burning intensity of the lean premixed flame with Le<1, the value of U at extinction is increased with increased K, as shown in Fig.7.

Figure 8 shows the flame flux ($\dot{m}_0$) and the flame position (x_f) of the rich propane/air flame (Φ_G=2.25, U=2.0 and Le = 0.95) as a function of K and γ under completely prevaporized water sprays ($r_i' \le r_c'$). It is seen that for a given U, an increase in γ leads to decreases in both $\dot{m}_0$ and x_f because a larger γ requires a larger amount of heat absorption from flame to droplets for upstream evaporation. Fig. 8 also indicates that the flame with a larger value of liquid loading has a diminished burning intensity and is extinguished by a smaller external heat loss.

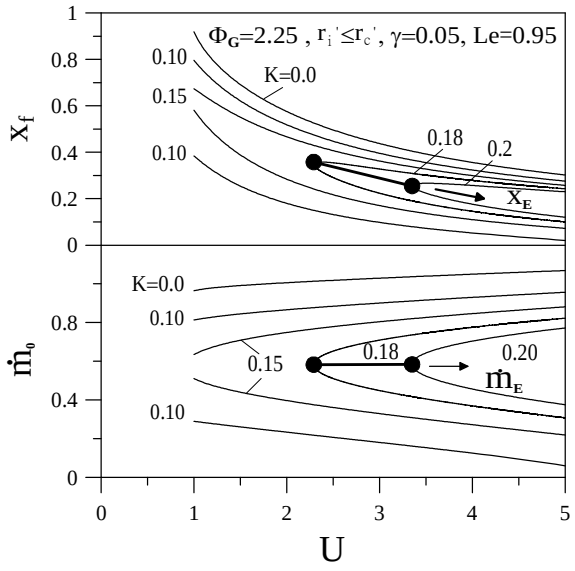

Fig. 7. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with the flow stretch (U) and the external heat loss (K) at γ=0.05 for rich propane/air flames under completely prevaporized water sprays.

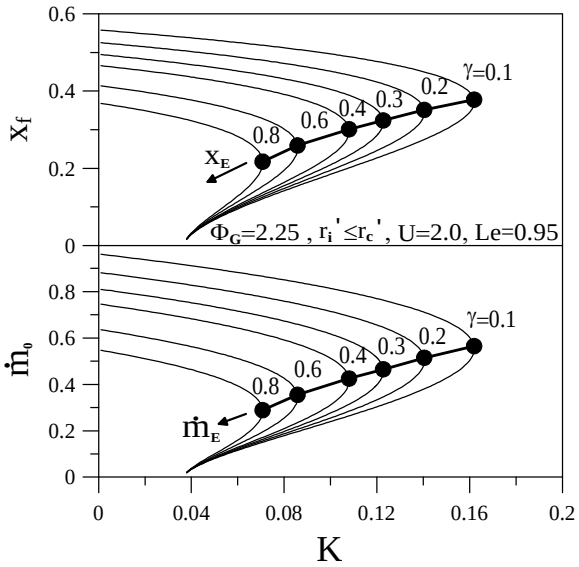

Fig. 8. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with liquid loading and the external loss for the rich propane/air flame under completely prevaporized water sprays.

Figure 9 shows the flame flux ($\dot{m}_0$) and the flame position (x_f) of the rich propane/air flames (Φ_G=2.25, K=0.2 and Le = 0.95) as a function of U and γ under completely prevaporized water sprays. Fig. 9 reveals that for a given γ, the increase of flow stretch results in the increase of $\dot{m}_0$ and the decrease of x_f, respectively. Note that flame extinction does exist if the flame experiences a sufficiently large external heat loss and suffers a small flow stretch. Fig. 9 further depicts that the turning points, relating to flame extinction, occur on the $\dot{m}_0$ and x_f curves when the flow stretch is small enough. This interesting phenomenon is because of the external heat loss overwhelming the heat gain by the Le<1 effect. For a fixed

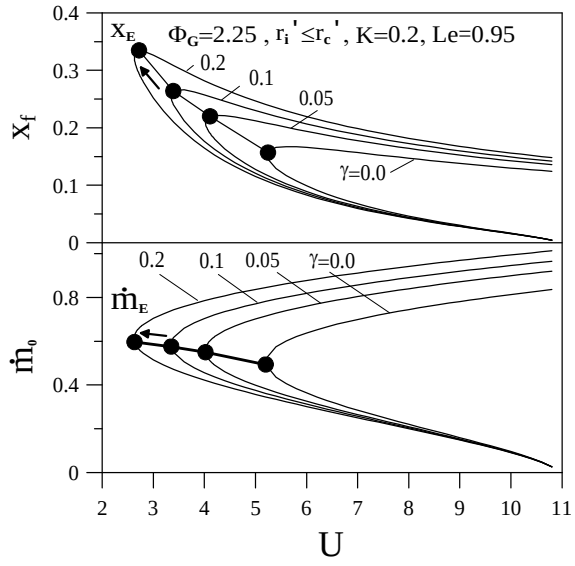

Fig. 9. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with the flow stretch (U) and the liquid loading (γ) for a rich propane/air flame at K=0.2 under completely prevaporized water sprays.

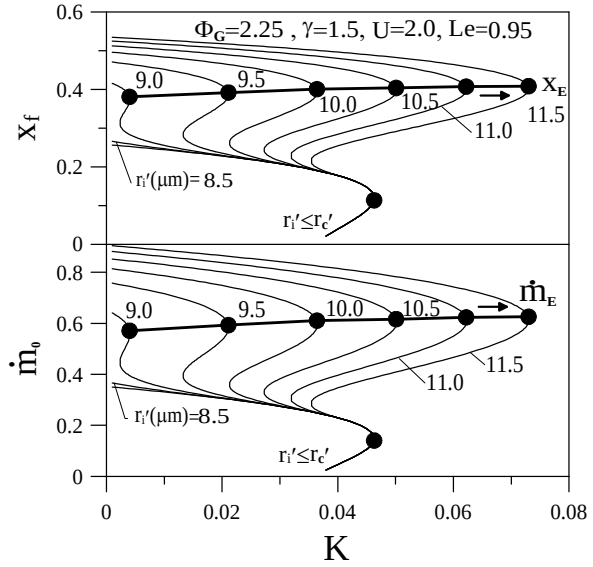

Fig. 10. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with the flow stretch and the droplet size for the rich propane/air flame under partially prevaporized water sprays.

amount of heat loss (K=0.2), the U value at extinction increases with decreasing γ. Finally, it is noteworthy that the Le<1 flame with completely prevaporized water sprays enduring a small flow stretch can be extinguished by external heat loss characterized by a C- shaped curve.

As shown in Figs. 7 and 9, extinction of the Le<1 flame with external heat loss may occur at low stretch. The numerical studies conducted by Guo et al. [18], Sung and Law [19] and Ju et al. [20, 21] with a detailed chemistry produced a C-shaped extinction curve and also showed the similar characteristic that the extinction at low stretch is caused by radiation heat loss.

The response of flame flux ($\dot{m}_0$) and flame position (x_f) on the external heat loss (K) is represented in Fig. 10, for the rich propane/air flame of Φ_G=2.25, γ=1.5, U=2 and Le = 0.95 with various initial droplet sizes. It is found that for a given flow stretch (U=2), both $\dot{m}_0$ and x_f increase with increasing r_i' or decreasing K. The former is due to the reduction of internal heat loss associated with the droplet gasification, the latter is caused by the decrease of the external heat loss. For a given value of r_i' (r_i'<9 μm), Fig. 10 shows that by increasing the external loss from a small value, the flame propagation flux initially influenced by the partially prevaporized spray is monotonically decreased and eventually ends at the completely prevaporized condition, therefore, flame extinction governed by the completely prevaporized spray occurs if the K is large enough. The curves for $r_i' \ge 9\,\mu m$ in Fig. 10 display that the $\dot{m}_0$ curve associated with the partially prevaporized spray is enlarged, and extinction of the Le<1 flame is therefore dominated by the partially prevaporized spray rather than the completely prevaporized one. Additionally, these curves for $r_i' \ge 9\,\mu m$ in Fig. 10 further demonstrate that with increasing r_i', both the flame propagation flux ($\dot{m}_E$) and the corresponding K at extinction are increased, and thus the flame position (x_E) at extinction is increased. Notably, we also find that if the droplet size is large enough, the flame propagation flux ($\dot{m}_E$) and flame position (x_E) at extinction can jump between the C-shaped curve (a double-valued function) governed by the completely prevaporized sprays and the W-shaped curve (a four-valued function) controlled by the partially prevaporized sprays.

For partially prevaporized sprays, the response of flame propagation flux ($\dot{m}_0$) and flame position (x_f) on the flow stretch is indicated in Fig. 11, with various initial droplet sizes, for a rich propane/air flame of Φ_G=2.25, γ=1.5, K=0.1 and Le =0.95. Fig. 11 shows that the flame propagation flux increases with increasing initial droplet size or flow stretch. The former is due to the reduction of internal heat loss coming from water vaporization, the latter is caused by the augmentation of the Le<1 effect. The curves for r_i'<9 μm in Fig. 11 reveal that the upper branch of the $\dot{m}_0$ curve controlled by the partially prevaporized sprays merges into that of the $\dot{m}_0$ curve governed by the completely prevaporized sprays and that flame extinction occurs at the condition of the flame enduring completely prevaporized sprays. Fig. 11 further shows that the rich propane/air flame (Le < 1) experiencing partially prevaporized water sprays can be extinguished by a small flow stretch, if droplet sizes are large enough ($r_i' \ge 9\,\mu m$). The W-shaped extinction curve (a four-valued function) which differs from the C-shaped one (a double-valued function) points out that the flame extinction is dominated by internal heat loss under the condition of Le < 1 flames experiencing smaller flow stretch. It is noteworthy that the flame propagation flux ($\dot{m}_E$) and flame position (x_E) at extinction jump between the C-shaped curve governed by the completely prevaporized sprays and the W-shaped curve controlled by the partially prevaporized sprays. Finally, Fig. 11 shows that under the influences of water spray, flow

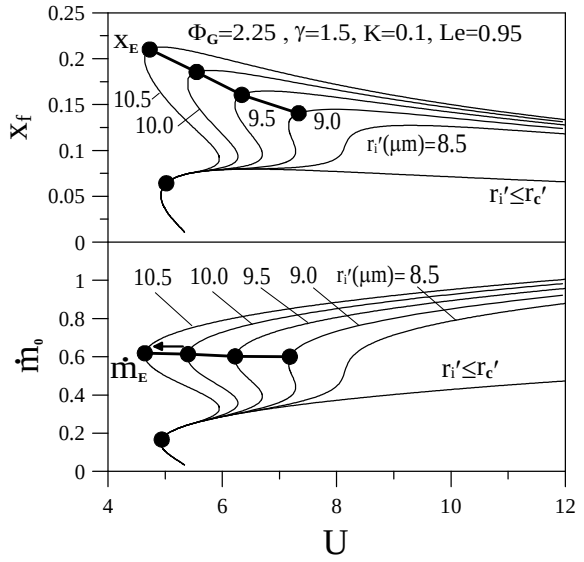

Fig. 11. Variations of the flame flux ($\dot{m}_0$) and the flame position (x_f) with the flow stretch and the droplet size for a rich propane/air flame (Φ_G =2.25, γ =1.5, K=0.1 and Le = 0.95) under partially prevaporized water sprays ($r_i' > r_c'$).

stretch and external heat loss, the Le<1 spray flames can be extinguished in the region far away from the wall. These interesting extinction characteristics for the Le<1 flame were not reported in the preliminary study [14].

Results of Fig. 10 (or Fig. 11) suggest that a Le<1 flame under the influence of a fixed amount flow stretch (or external heat loss) can be quenched by a constant amount heat loss comprising of a larger r_i' corresponding to a smaller internal heat loss and a larger K representing a larger amount of external heat loss (or a smaller flow stretch corresponding to the suppression of the Le<1 effect). The interesting characteristic of the abrupt change on $\dot{m}_E$ or x_E from the completely prevaporized spray to the partially prevaporized water spray in Figs. 10 and 11 further emphasizes the significant influence of the droplet size on the flame extinction. Finally, it is important to note that the W-shaped extinction curve shown in Figs. 10 and 11 represents the combination of solutions of completely and partially prevaporized spray, and always occurs when the rich propane/air flame experiences a partially prevaporized water spray composed of a sufficiently large r_i' and a large enough γ .

4. CONCLUSIONS

An extinction theory for stretched premixed flames with inert sprays was developed using activation energy asymptotics, in which the influences of liquid spray, flow stretch, Lewis number and external heat loss on the extinction of propane/air flames are explored. In the analysis, a completely prevaporized mode and a partially prevaporized mode are identified. Concluding remarks are summarized as follows:

(1)The internal heat loss embedded in the water spray provides heat loss for the system. The flow stretch weakens the burning intensity of the lean propane/air flame (Le>1), but strengthens that of the rich propane/air flame (Le<1).

(2)Flame extinction characterized by a C-shaped curve for the lean propane/air flame with Le>1 is mainly dominated by the flow stretch or external heat loss and is only slightly modified by the internal heat loss, while the W-shaped extinction curve for the rich propane/air flame with Le<1 is strongly influenced by internal heat loss.

(3)The lean propane/air flame with Le>1 can be extinguished with or without external heat loss. Both the external heat loss and the flow stretch are found to strongly dominate the tendency for flame extinction characterized by a C-shaped curve. On the other hand, the burning intensity weakened by the external heat loss or the flow stretch can be diminished if the water spray contains a larger amount of liquid loading or a smaller initial droplet size.

(4)In the absence of external heat loss, no extinction occurs under the influence of flow stretch for the rich propane/air flame (Le<1). Whereas, the rich propane/air flame (Le<1) with the completely prevaporized water sprays enduring small flow stretch can be extinguished by the external heat loss characterized by a C-shaped extinction curve. Furthermore, the W-shaped extinction curve which differs from the C-shaped one occurs in the presence of external heat loss if the Le<1 flames enduring a small flow stretch and experiencing a partially prevaporized water sprays composed of the large enough liquid loading and sufficiently large droplet size.

(5)For the rich propane/air flame (Le<1) with external heat loss, the flame propagation flux ($\dot{m}_E$) and flame position (x_E) at extinction can jump between the C-shaped curve (governed by the completely prevaporized sprays) and the W-shaped curve (controlled by the partially prevaporized sprays) in response to varying the liquid loading or the droplet size. These interesting characteristics further emphasize the significant influences of liquid loading and droplet size on the flame extinction.

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NOMENCLATURE

Dimensional quantities

B'	preexponential factor
C'_{PG}	specific heat of the gaseous mixture
C'_{PL}	specific heat of liquid
D'	mass diffusion coefficient
E'_a	activation energy
L'	separation distance (Fig. 1)
ℓ'_D	thickness of the diffusion zone
$\tilde{\bar{M}}'$	average molar mass
P'	pressure
Q'	heat of combustion per unit mass of fuel
$\tilde{R}$	universal gas constant

r_i' initial droplet radius

r_c' critical initial droplet size

Nondimensional quantities

$\bar{A}$ equation (1)

h_{LG} latent heat of vaporization, $Q=Q'/(C_{PG}'T_i')$

K external heat loss parameter

$\bar{K}$ flow stretch parameter

Le Lewis number

$\dot{m}_0$ axial mass flux (ρu), $\rho' u' / \rho_i' s_L^0$

T temperature, T'/T_i'

T_a activation temperature, $E_a'/\tilde{R}T_i'$

T_{ad} adiabatic flame temperature, T_{ad}'/T_i'

U axial velocity at the burner exit, u_i'/s_L^0

u, v axial and radial velocities, $u=u'/s_L^0$, $v=v'/s_L^0$

$\dot{W}$ equation (8)

x, y axial and radial coordinates, $x=x'/L'$, $y=y'/L'$

Y mass fraction, $Y_F=Y_F'$, $Y_O=Y_O'/\sigma$

z density ratio, ρ_G'/ρ'

Greek symbols

γ $(1-z_i)/\delta$

δ small expansion parameter, ℓ_D'/L'

ε small expansion parameter, $\tilde{R}T_{ad}'/E_a'$

λ' thermal conductivity

ξ stretch variable for the diffusion zone, $(x-x_f)/\delta$

Φ equivalence ratio

σ stoichiometric ratio

Γ defined in equation (11)

Subscripts

b boiling state

E state at extinction

e state at which droplet is completely vaporized

f flame front

F , O fuel and oxygen

G , L gas and liquid phases

i i=F and O in lean and rich flame

j j=O and F in lean and rich flame

v state at which evaporation initiates

0, 1 zeroth and first order solutions

$-\infty$, ∞ initial and final states

Superscripts

+ downstream of the flame

′ dimensional quantities

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