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INNER STRUCTURE OF BICOMPONENT FUEL DIFFUSION FLAMES: EXTINCTION CONDITION

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Abstract. *The analysis addresses the extinction problem of diffusion flames in which two fuels are consumed simultaneously. A single step finite rate reaction is considered for each fuel. The extinction problem is described by the large activation energy asymptotics, assuming that the ratio of the activation energies for the two reactions is order unity. Thus, the two chemical reactions take place inside the same zone in the flow field. The present model is characterized by two new parameters. The first parameter, Δ, is the ratio of the Damköhler numbers of the second and first reactions. It measures the reactivity of the second reaction in terms of the first reaction reactivity. The second parameter, A_E, is the ratio of the activation energy of the second reaction to the activation energy of the first reaction. It specifies the thermal sensitivity of the second reaction in terms of the thermal sensitivity of the first reaction. For equal reactivities ($\Delta = 1$) and equal thermal sensitivities ($A_E = 1$) the classical results (Liñán, 1974) are recovered. The results obtained show a flammability limit for bicomponent fuel diffusion flames.*

Keywords: *large activation energy asymptotics, extinction, diffusion flame, internal flame structure, bicomponent fuel.*

1. Introduction

Extinction of flames is the main subject in many areas of combustion. For some of them, the extinction is forced to occur as in any kind of fire, but for other areas it is avoided as for instance the controlled burning fuel inside combustion chambers. Despite the large number of works that have been done on the extinction flames, there are still questions to be examined.

According to the literature, the analytical description of the flame extinction mechanism has been only performed in asymptotic conditions. By assuming that the reactions are performd in one global step and using the asymptotic expansion based on the Damkhöler number, Fendell, 1965, described systematically the inner diffusion flame structure and determined the extinction. The extinction condition occured at one turning point of the S shaped curve for the maximum temperature as a function of Damkhöler number. Since the thermal dependence of the reactions was excluded in his analysis, the results provided by the model did not represent well the results from the experimental studies. Liñán, 1974, included the thermal dependence of the chemical reaction by making use of asymptotic expansion based on the large activation energy. His improvement in the analytical model was able to reproduce the extinction condition in the same order of magnitude of that observed by the experimental results. More recently, Peters and Williams, 1987, described asymptotically the inner flame structure based on the reaction rate ratios, by considering the reaction being represented by a reduced kinetic mechanism with four global steps. Because of the complexity of this kinetic mechanism, the decription of the flame structute probem becomes large as compared to the two mentioned models. However, the results from this complex model present a better agreement with the experimental results.

Despite the improvement on the flame structure models, from which the extinction condition is determined, very few works have been devoted to describe the flame generated by the burning of multicomponent fuels. Hamnis and Seshadri, 1984, analyzed the extinction of bicomponent liquid fuel, which is burned in a pool configuration with air stream being directed against the liquid surface. Based on the knowledge of chemical kinetic parameters, i.e. activation energy and frequency factor, of each fuel near the exitnction condition (Krishnamurthy et al, 1976), they developed a mixing rule that determined the overall chemicall kinetic rate parameters that represent the mixture of fuels as one hypothetical fuel. By having those parameters, the large activation energy asymptotic was applied and the results showed a good agreement with the experimental results.

The focus of this paper is to investigate the mechanism of extinction of bicomponent fuel diffusion flames. The model presented in this analyis will follow the large activation energy asymptotics.

2. External Flow Description

As pointed out by Liñán, 1974, the inner flame structure presents no dependence on the geometry that characterizes the outer flame structure (flowfield). The flowfield information necessary to perform the inner structure analysis is the mass fluxes, energy fluxes and the temperature at the flame. These properties are provided from the steady, axisymmetric, laminar counterflow model. A description of the counterflow diffusion flame model is given in detail by Tsuji, 1982. The specific flowfield properties for the bicomponent-fuel, counterflow diffusion flame were specified by Fachini, 2001. In his analysis the assumptions of infinitely fast chemical reaction (Burke-Shumman kinetics) is assumed. Thereby, mixture fraction and excess enthalpy functions were employed in order to describe the problem.

The chemical reaction of each component of the fuel is assumed to occur in a single global step as follows,

$$F_i + s_i O_2 \rightarrow h_i H_2O + c_i CO_2, \quad i = 1, 2, \tag{1}$$

in which s_i, h_i and c_i are the stoichiometric reaction coefficients defined as the mass consumed or produced by the consumption of a unit mass of fuel i. Here the bicomponent fuel is formed by the mixture of n-heptane and hydrogen. Thus, for $i = 1$ (n-heptane-oxygen reaction), s_1 is 3.52, h_1 is 3.08 and c_1 is 1.44, and for $i = 2$ (hydrogen-oxygen reaction), s_2 is 8.0, h_2 is 9.0 and c_2 is zero.

The reaction rates are specified by

$$w_i = Da_i \varrho_i^{\beta_{i1}+\beta_{i2}} y_O^{\beta_{i1}} y_i^{\beta_{i2}} exp(-\theta_{ai}/\theta), \quad i = 1, \ 2, \tag{2}$$

in which β_{i1} and β_{i2} are the global order of reaction i, adopted equal to one ($\beta_{ij} = 1$, $i = 1, 2$ and $j = 1, 2$) and $\theta_{ai} = E_{ai}/RT_0$ is the nondimensional activation energy of the reaction i. $\theta = T/T_0$ and $\varrho = \rho/\rho_0$ are the nondimensional temperature and density, respectively. The subscript 0 represents the condition at the nozzle from where the air comes and the subscript 1 represents the condition at the nozzle from which the bicomponent fuel comes. The oxygen mass fraction y_0 and the fuel mass fractions y_1 and y_2 are rescaled to express conveniently the conservation equations for this analysis. Their definitions are given by

$$y_0 \equiv \frac{Y_{O_2}}{Y_{O_2 0}}, \quad y_i \equiv \frac{s_i Le_O Y_{Fi}}{Y_{O_2 0} Le_i}.$$

The Damkhöler number Da_i, defined as the ratio of the characterisitic flow time to the characteristic chemical time, for the reaction i is expressed by

$$Da_i \equiv (B_i l / v_0)(\rho_0 Y_{O_2 0})^{\beta_{i1}+\beta_{i2}-1} Le_i^{\beta_{i2}} / (s_i Le_O)^{\beta_{i2}-1}.$$

The total heat release by bicomponent fuel burning is $q_1.w_1 + q_2.w_2$, in which the nondimensional heat q_i is defined as

$$q_i \equiv Q_i Y_{O_2 0} / c_p T_0 s_i Le_O.$$

in which Q_1 is $4.495 \ 10^4 (J/Kg)$ (n-heptane) and Q_2 is $1.198 \ 10^5 (J/Kg)$ (hydrogen).

The characteristic of the counterflow problem is given by the following properties: the space between the two nozzles is taken as being $l = 2cm$ and the velocity and the temperature (373 K) are the same for the two streams at the nozzles. The transport coefficients are assumed to be a function of temperature, according to $\rho D_i / \rho_0 D_{i0} = k/k_0 = \mu/\mu_0 = (T/T_0)^n$ in which D_i, k and μ are diffusion coefficient of species i, thermal conductivity and viscosity, respectively. The Lewis number, defined as the ratio of thermal diffusivity to the diffusion coefficient $(k_0/c_p\rho_0)/D_{i0}$, is different from unity ($k_0 = 0.0303 J/m.K.s$). The Lewis numbers for n-heptane, hydrogen, oxygen, water vapor and carbon dioxide are 1.7, 0.5, 1.1, 0.85, 1.2, respectively. The specific heat at constant pressure is considered constant at 1.25 J/g.K.

The radiative energy losses, which are realesed in the CO_2 and H_2O, as well as the approximation of optically thin transparent gases are assumed in present analysis.

3. Internal Flame Structure Description

In this analysis the large-activation-energy asymptotical description follows identical procedure developed by Liñán, 1974, independently of the number of fuels consumed in the diffusion flame. Also, the same nomenclature is adopted in this work, except for a few modifications introduced in order to identify the bicomponent fuel burning.

Two new parameters appear in this description of the inner flame structure estabilished by a bicomponent fuels. One of them, Δ, is the ratio of the reactivity of the reaction 2 to the reactivity of the reaction 1, which measures the rate reaction 2 is performed in comparison to the reaction 1. The other one, A_E, is the ratio of the activation energy of the reaction 2 to the activation energy of the reaction 1, which compares the thermal sensitivity of the reaction 2 to that of the reaction 1. It is worthwhile to mention that these parameters do not appear in Liñán's analysis (1974).

In order to show the main processes of the extinction of bicomponent fuel diffusion flames, the mixture is composed by hydrogen and n-heptane, the light and heavy species, respectively. The model developed in this work can be applied for

determining, in first approximation, the burning behavior of n-heptane in the presence of hydrogen, besides for specifying the extinction conditions. In order to use the asymptotic method in the solution of this problem, the activation energies of the two reactions are considered large.

This work will concentrate on the case defined by $\theta_{a2} \sim \theta_{a1} \gg 1$. In this way the expression $\theta_{a1}/\theta_{a2} = A_E = O(1)$ is satisfied and the two reactions are equally influenced by temperature.

The reaction zone is correctly described by the following variables (Liñán, 1974),

$$
\begin{aligned}
\theta &= \theta_f &-& \varepsilon(\Theta + \gamma\xi)/\delta_1^{1/(1+\beta_{11}+\beta_{12})} &+& o(\varepsilon) \\
y_{O_2} &= && \varepsilon d_0 \Psi_0/m\delta_1^{1/(1+\beta_{11}+\beta_{12})} &+& o(\varepsilon) \\
y_{F_1} &= && \varepsilon d_1 \Psi_1/m\delta_1^{1/(1+\beta_{11}+\beta_{12})} &+& o(\varepsilon) \\
y_{F_2} &= && \varepsilon d_2 \Psi_2/m\delta_1^{1/(1+\beta_{11}+\beta_{12})} &+& o(\varepsilon)
\end{aligned}
\tag{3}
$$

in which

$$
m \equiv \frac{d_\theta^- + d_\theta^+}{2}, \quad \gamma \equiv 1 - \frac{2d_\theta^-}{d_\theta^- + d_\theta^+}, \quad \delta_1 \equiv Da_1\left(\frac{\varepsilon}{m}\right)^{1+\beta_{11}+\beta_{12}}\frac{d_0^{\beta_{11}}d_1^{\beta_{12}-1}}{\theta_f^{\alpha+\beta_{11}+\beta_{12}}}e^{-\theta_{a1}/\theta_f}, \quad \varepsilon \equiv \frac{\theta_f^2}{\theta_{a1}}
$$

The values of $d_0, d_1, d_2, d_\theta^-$ and d_θ^+, specified by the outer flame structure analysis (Fachini, 2001), are defined by

$$
d_0 \equiv -\left.\frac{dy_{O_2}}{dz}\right|_{z=z_f^-}, \quad d_1 \equiv \left.\frac{dy_{F_1}}{dz}\right|_{z=z_f^+}, \quad d_2 \equiv \left.\frac{dy_{F_2}}{dz}\right|_{z=z_f^+}, \quad d_\theta^- \equiv \left.\frac{d\theta}{dz}\right|_{z=z_f^-}, \quad d_\theta^+ \equiv -\left.\frac{d\theta}{dz}\right|_{z=z_f^+},
$$

represent the oxygen, n-heptane and hydrogen fluxes to the flame and the heat fluxes from the flame, respectively. The superscripts $-$ and $+$ refer to the oxygen and fuel sides of the flame, respectively.

Inside the flame, variations of temperature Θ, oxygen mass fraction Ψ_0, n-heptane mass fraction Ψ_1 and hydrogen mass Ψ_2 are of order unity to variation of same order in the spacial coordinate

$$
\xi = \frac{m\delta_1^{1/(1+\beta_{11}+\beta_{12})}(z - z_f)}{\varepsilon}
\tag{4}
$$

In which m and γ are chosen to make the derivative of temperature Θ symmetric on the line $\xi = 0$ and normalized as $\xi \to -\infty$ and $\xi \to \infty$.

The species and energy conservation equations written in the variables specified by Eqs. (3) and (4) are given by

$$
\frac{d^2}{d\xi^2}\begin{Bmatrix} m(\Theta + \gamma\xi) \\ d_0\Psi_0 \\ d_1\Psi_1 \\ d_2\Psi_2 \end{Bmatrix} = \begin{Bmatrix} q_1d_1 & q_2d_2 \\ d_1 & d_2 \\ d_1 & 0 \\ 0 & d_2 \end{Bmatrix}\begin{Bmatrix} \Psi_0^{\beta_{11}}\Psi_1^{\beta_{12}}exp[-(\Theta - \gamma\xi)\delta_1^{-1/(1+\beta_{11}+\beta_{12})}] \\ \Delta\Psi_0^{\beta_{21}}\Psi_2^{\beta_{22}}exp[-A_E(\Theta - \gamma\xi)\delta_1^{-1/(1+\beta_{11}+\beta_{12})}] \end{Bmatrix}
\tag{5}
$$

in which Δ is defined as being,

$$
\Delta \equiv \frac{Da_2Ped_0^{\beta_{21}}d_2^{\beta_{22}-1}e^{-\theta_{a2}/\theta_f}}{\theta_f^{\alpha+\beta_{21}+\beta_{22}}\delta_1^{(1+\beta_{21}+\beta_{22})/(1+\beta_{11}+\beta_{12})}}\left(\frac{\varepsilon}{m}\right)^{1+\beta_{21}+\beta_{22}}
$$

By combining Eqs. (5) in an appropriate form to eliminate the source terms, one obtains two functions. These functions are passive functions that do not change by the chemical reactions. In term of matricial operation, those combinations are represented by the multiplication of the matrix

$$
\begin{Bmatrix} 0 & -1 & 1 & 1 \\ -1 & 1 & q_1-1 & q_2-1 \end{Bmatrix}
\tag{6}
$$

to Eq. (5), which leads to the mixture fraction and enthalpy excess in the inner flame structure variables,

$$
d_1\Psi_1 + d_2\Psi_2 + d_0\Psi_0 = d_Z\xi,
\tag{7}
$$

$$
(q_1-1)d_1\Psi_1 + (q_2-1)d_2\Psi_2 - d_0\Psi_0 - m(\Theta + \gamma\xi) = d_H\xi.
\tag{8}
$$

d_Z and d_H are the derivative of the mixture fraction Z, defined as $y_1 + y_2 - y_0 + 1$, and of the excess of enthalpy H, defined as $(q_1-1)y_1 + (q_2-1)y_2 + y_0 + \theta$. Since the functions Z and H as well as their first derivative are continous, the relations among the species and energy fluxes at the flame

$$
d_Z = d_1 + d_2 = d_0, \quad d_H = (q_1-1)d_1 + (q_2-1)d_2 - d_\theta^+ = -d_0 + d_\theta^-
\tag{9}
$$

are determined.

By combining Eqs. (7) and 8) and taking into account Eq. (9), the following relations,

$$\Psi_0 = \frac{(1 - q_1/q_2)}{(1 + d_2/d_1)}(\Psi_1 - \xi) + \frac{1}{2}\left(1 + \frac{q_1 d_1}{q_2 d_2}\right)\frac{d_2/d_1}{(1 + d_2/d_1)}(\Theta - \xi) \tag{10}$$

$$\Psi_2 = \frac{1}{2}\left(1 + \frac{q_1 d_1}{q_2 d_2}\right)(\Theta + \xi) - \frac{q_1 d_1}{q_2 d_2}\Psi_1 \tag{11}$$

are found. These relations determine the value of the oxygen and hydrogen mass fractions as a function of the temperature and n-heptane mass fraction.

Relations (10) and (11) are employed to reduced the system of equations given by Eqs. (5). It is choose to work with the energy and fuel 1 conservation equations, which must satisfied the following boundary conditions

$$\frac{d\Theta}{d\xi} = -1, \qquad \frac{d\Psi_1}{d\xi} = 0 \qquad \text{for} \quad \xi \to -\infty \tag{12}$$

$$\frac{d\Theta}{d\xi} = 1, \qquad \frac{d\Psi_1}{d\xi} = 1 \qquad \text{for} \quad \xi \to \infty \tag{13}$$

The range of δ_1 for which the flame is stable is found for given values of γ, Δ and A_E. This range has a minimum value that corresponds to the extinction condition of the bicomponent fuel diffusion flame.

4. Results and Comments

For the results that will be shown in this work, the mixture of fuels is composed in a such way that the n-heptane mass fraction is 0.25 and the hydrogen mass fraction is 0.01. In all the cases analyzed the diluting gas was nitrogen. For this composition, the mean value of the parameters γ and d_2/d_1 are 0.508 and 0.464, respectively. Since these parameters present a negligible variation in the whole range of the jet velocity ($0.2 - 4 m/s$), the numerical simulations on the flame structure are performed considering γ and d_2/d_1 constant and equal to their mean values. Moreover, the value of the other parameters are: $q_1 d_1/m = 1.295$, $q_2 d_2/m = 0.705$, $q_1/q_2 = 0.852$ and $q_1 d_1/q_2 d_2 = 1.836$. Note that, according to the definition of m and from Eq. (9), $q_1 d_1 + q_2 d_2/m$ is equal to 2 for a mixture of any two fuels in any composition.

Under the assumptions for the large activation energy asymptotics, extinction is caracterized by enormous amount of fuel and oxygen scaping through the flame without reacting. Recalling that the problem is scaled by ε, thus the mathematical condition for the extinction is $\Psi_1 = \to \infty$ and/or $\Psi_2 \to \infty$ as $\xi \to -\infty$ and $\Psi_0 \to \infty$ as $\xi \to \infty$. The extinction process depends on the set of chemical and physical properties which are gathered in the modified Damköhler number δ_1. For the specific case of the bicomponent fuel diffusion flame the extinction Damköhler number $\delta_{1\ ext}$ depends on chemical and physical properties expressed by the parameters γ, A_E and Δ; $\delta_{1\ ext} = \delta_{1\ ext}(\gamma, A_E, \Delta)$. Note that, the extinction Damköhler number $\delta_{1\ ext}$ for one-fuel diffusion flame is a function only of γ; $\delta_{1\ ext} = \delta_{1\ ext}(\gamma)$ (Liñán, 1974).

Figure 1 shows the n-heptane and hydrogen mass fractions at $-\xi \gg 1$ for four values of Δ. It is seen for all curves that the n-heptane leakage, $\Psi_{1\ -\infty}$, increases fast to infinity at $\delta_1 = \delta_{1\ ext}$, but the hydrogen leakage, $\Psi_{2\ -\infty}$, reaches a finite value at the extinction. These results reveal that the n-heptane is the species responsable for the stability of the flame. Mathematically, the solution of the inner flame structure problem is not found for $\delta_1 < \delta_{1\ ext}$.

The amount of the n-heptane, $\Psi_{1\ -\infty}$, and of the hydrogen, $\Psi_{2\ -\infty}$ scaping by the flame at the extinction is displayed in Fig. 2. It is seen that for Δ larger than 2.6 the hydrogen leakage through the flame vanishes. This result is a signal that the flame structure is not modify significantly for $\Delta > 2.6$ because hydrogen is completely consumed in the flame. Physically, by increasing the value of Δ, the reaction 2 has an increasing responsability for maintaining the flame stability and, hence, the hydrogen leakage has to decrease. Conversely, n-heptane leakage can increase without affecting the flame stability. It is, also, noted that descreasing Δ from 1, the hydrogen leakage increases but n-heptane leakage deacreses (see Fig. 3) because the responsability of the reaction 1 for supporting the flame increases. The flame seems not to be stable for $\Delta < 0.6$ as a consequence of large hydrogen leakage as showing in Fig. 2. Therefore, it is possible to find a stable diffusion flame for the condictions that satisfy $0.6 < \Delta$ (as seen in Fig. 3). This result can be understood as a flammability limit for bicomponent fuel diffusion flames.

For the sake of having an approximation for the extinction Damköhler number $\delta_{1\ ext}$ without the necessity of integrating the system of equations (5), (10) to (13), the Fig. 4 is presented. The parameter δ_1^*, defined to include the Δ as $\delta_{1\ ext}\cdot(q_1 d_1 + \Delta q_2 d_2)/(q_1 d_1 + q_2 d_2)$, has a small variation in the range $0.6 < \Delta < 2.6$. Thus it is a good approximation $\delta_1^* = 1.7$.

Figures 5 and 6 show the behavior of the flame extinction conditions as a function of A_E. For the reaction 2 being less thermal sensitive than reaction 1, $A_E < 1$, the hydrogen leakage through the flame is smaller as A_E decreases because the hydrogen has an abroad zone to react with oxygen. Figure 6 reveals a low limit for $A_E = 0.72$ beyond that the flame does not depedend strongly on the hidrogen , since it is completely consumed inside the reaction zone. The numerical simulations did not go further $A_E = 1.15$. This upper limit stays without a resonable understanding.

It is worthwhile to note that for $\Delta = A_E = 1$, the Liñán's (1974) results have to be found because each reaction has the same contribution on the flame stability. However, for his model, the extinction Damköhler number $\delta_{1\ ext}$ is 0.772 for
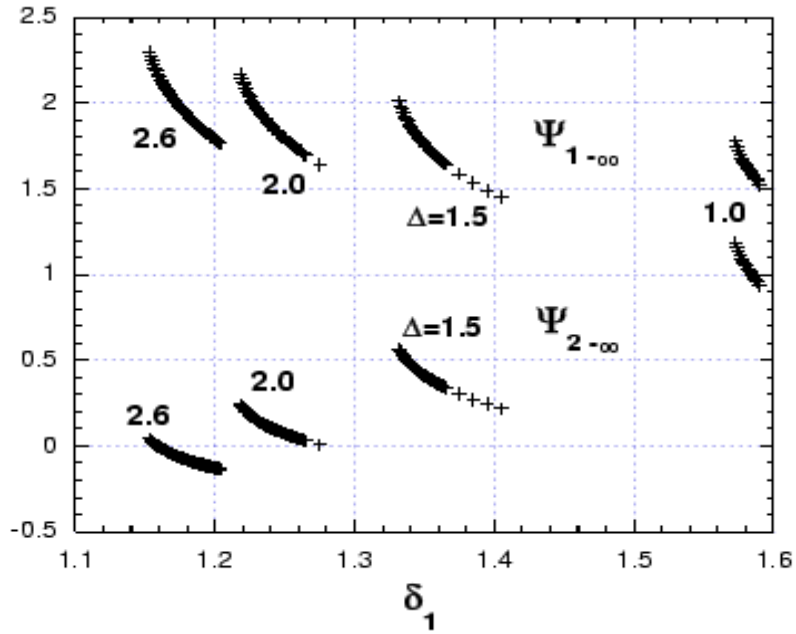
Figure 1: Amount of n-heptane ($\Psi_{1-\infty}$) and of hydrogen ($\Psi_{1-\infty}$) scaping by the flame as a function of the modified Damkhöler number δ_1. These data are obtaining for the following condictions: $A_E = 1$, $m = 0.508$, $d_2/d_1 = 0.464$, $q_1d_1/q_2d_2 = 1.836$, $q_1d_1/m = 1.295$ and $q_2d_2/m = 0.705$.

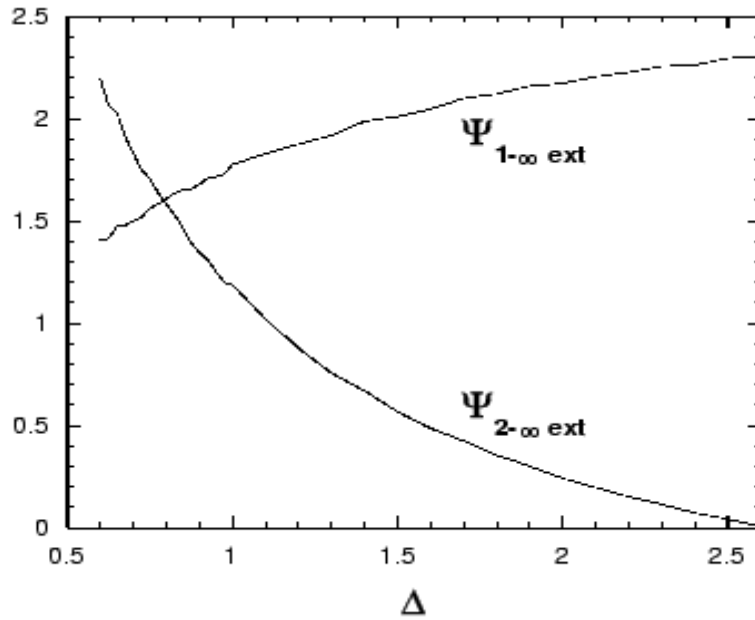Figure 2: Amount of n-heptane ($\Psi_{1-\infty\ ext}$) an of hydrogen ($\Psi_{2-\infty\ ext}$) scaping by the flame at extinction. The variation of $\Psi_{2-\infty\ ext}$ with Δ close to $\Delta = 0.6$ is large, showing a stability limit for the flame. The conditions for these data are: $A_E = 1$, $m = 0.508$, $d_2/d_1 = 0.464$, $q_1d_1/q_2d_2 = 1.836$, $q_1d_1/m = 1.295$ and $q_2d_2/m = 0.705$.
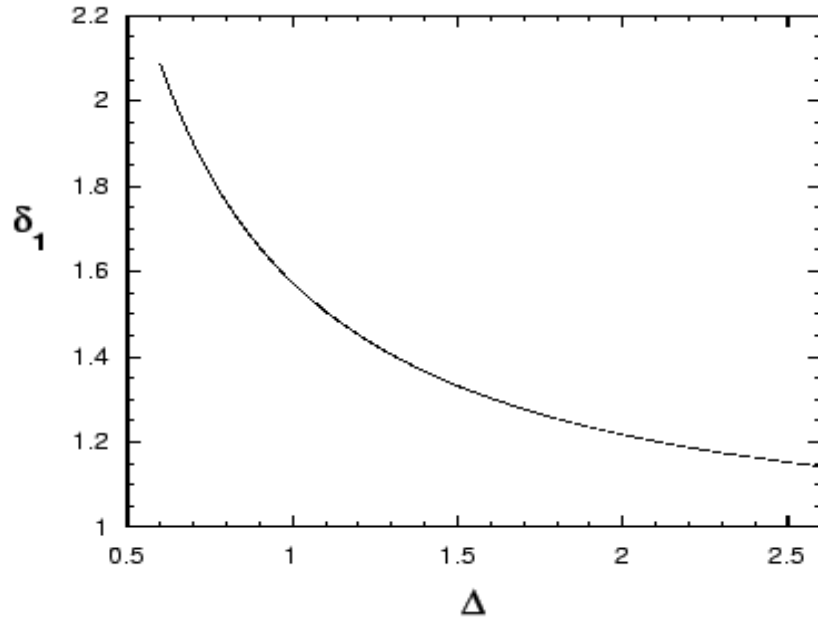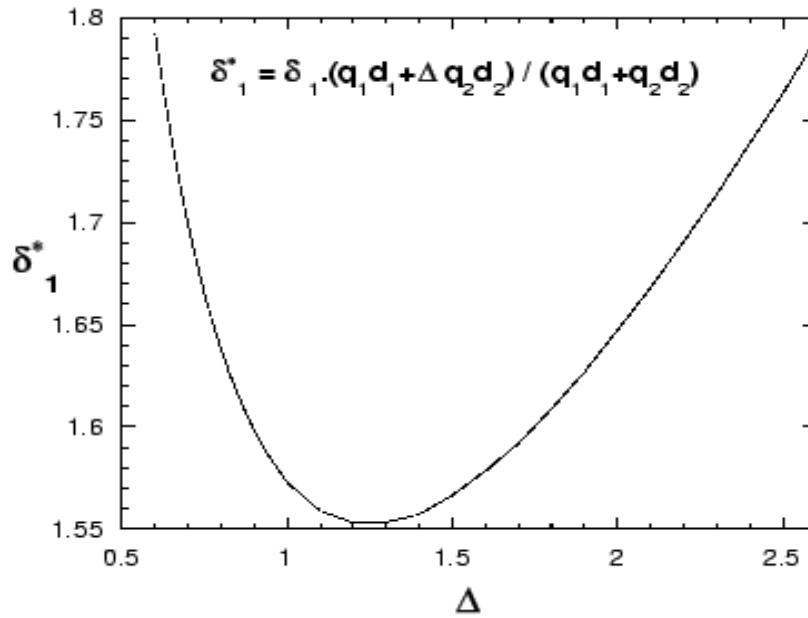
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Figure 3: Extinction Damkhöler number $\delta_{1\ ext}$ as a function of Δ. The condictions for these data are: $A_E = 1$, $m = 0.508$, $d_2/d_1 = 0.464$, $q_1d_1/q_2d_2 = 1.836$, $q_1d_1/m = 1.295$ and $q_2d_2/m = 0.705$.

$$\delta^*_1 = \delta_1 \cdot (q_1d_1 + \Delta q_2d_2) / (q_1d_1 + q_2d_2)$$

Figure 4: The variation of δ^*_1, defined as $\delta_1 \cdot (q_1d_1 + \Delta q_2d_2)/(q_1d_1 + q_2d_2)$, as a function of Δ. The condictions for these data are: $A_E = 1$, $m = 0.508$, $d_2/d_1 = 0.464$, $q_1d_1/q_2d_2 = 1.836$, $q_1d_1/m = 1.295$ and $q_2d_2/m = 0.705$.
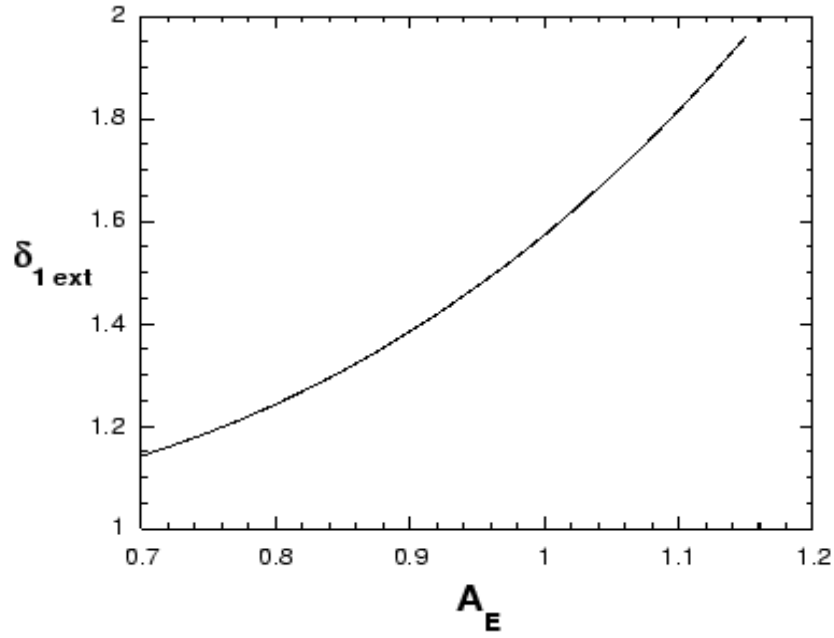
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Figure 5: Extinction Damkhöler number $\delta_{1\ ext}$ as a function of A_E. The condictions for these data are: $\Delta = 1$, $m = 0.508$, $d_2/d_1 = 0.464$, $q_1 d_1/q_2 d_2 = 1.836$, $q_1 d_1/m = 1.295$ and $q_2 d_2/m = 0.705$.
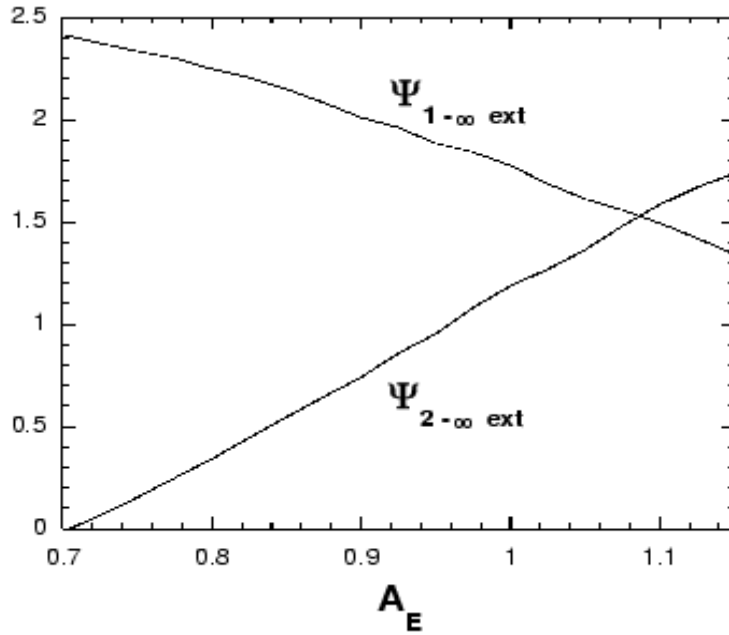

Figure 6: Amount of n-heptane ($\Psi_{1-\infty\ ext}$) and hydrogen ($\Psi_{2-\infty\ ext}$) scaping by the flame at the extinction as a function of A_E. The condictions for these data are: $A_E = 1$, $m = 0.508$, $d_2/d_1 = 0.464$, $q_1 d_1/q_2 d_2 = 1.836$, $q_1 d_1/m = 1.295$ and $q_2 d_2/m = 0.705$

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$\gamma = 0.508$ and the result for this model is $\delta_{1\ ext} = 1.573$. The difference in the results of about two times is due to the difference in the Damkhöler number definition adopted in the two models. In Liñán's model the heat released $(q_1 d_1 / m)$ is incorporated in the Damkhöler number, but in this model it is not possible to perform the same handling because the fuel consists of more than one component and also the heat released of the reactions are not the same.

5. Conclusions

This analysis describes asymptotically the internal structure of bicomponent fuel diffusion flames by using the large activation energy asymptotics. The model developed was able to determine the extinction condition for the burning of a mixture of n-heptane and hydrogen. By the fact that these two fuels are burning in two separated reactions, two parameters are enough to express the difference between the reactions, the reactivity Δ and the thermal sensitivity A_E. An extension in the model for considering more reactions is immediate. By adding of an extra fuel in the mixture, an extra pair of parameters (Δ_n and $A_{E\ n}$) will appear in the model due to the the reactivity and thermal sensitivity for the reaction of this fuel..

This model was able to recover Liñán's (1974) results for $\Delta = A_E = 1$.

The results of the bicomponent fuel model show that increasing the reactivity of reaction 2 such that $\Delta > 2.6\ (A_E = 1)$ is fruitless because beyond that upper limit there is no scape of fuel 2 by the flame, i.e. fuel 2 is completely consumed inside the flame zone. Also, there is a lower limit at $\Delta = 0.6$. Close to this limit the scape of fuel 2 becomes large, indicating that the flame cannot exit beyond that limit. It is a flammability limit. The variation of the thermal sensitivity parameter A_E shows that there is a lower limit, $A_E = 0.72$, beyond that the reaction 2 has no influence on the internal flame structure because the fuel 2 is consumed completely inside the flame.

6. Acknowledgments

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