QUASI-STEADY DROPLET COMBUSTION WITH DIFFERENT CONSTANT VALUES FOR CONSTANT PRESSURE SPECIFIC HEAT IN EACH FLAME SIDE

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Abstract. This work presents an externsion of the classical droplet combustion theory. Based on the infinite reaction rate, the Shvab-Zel'dovich formaulation is applied. This formulation permits to study analytically problems with nonunity Lewis number and the transport coefficients dependent on temperature. An extension for it is proposed in which different constant pressure specific heat in each side of the flame is considered. Although the formulation admits varible transport coefficient, nonunity Lewis number and different constant values for the constant pressure specific heat in each side of the the flame, the problem has an analytical solution.

Keywords: droplet combustion, diffusion flame, Zel'dovich formulation, Liñán formulation, flamelet formulation

1. INTRODUCTION

The quasi-steady behavior in the gas phase close to the droplet surface, compared to the liquid phase behavior, makes the fluid-dynamical description of the droplet problem relatively simple. The sucess of the quasi-steady model is measured by the determination of the linear deacreasing of the square droplet radius with time (d^2 law) (Spalding, 1953; Godsave, 1953; Goldsmith and Penner, 1954; Kumagai and Isoda, 1956). The present work is an extension of the classical droplet combustion theory; nonunity Lewis number, variable transport coefficients and different constant values for the constant pressure specific heat in each side of the flame are considered. Even with these asumptions, the problem has an analytical solution. To achieve this goal the Shvab-Zeldovich formalution is extended, Liñán formulation and the flamelet concept are used to remove the chemical term, to make continuous the coefficients of the excess enthalpy and mixture fraction equations and to write the excess enthalpy function in terms of the mixture fraction function.

The first descriptions of the droplet combustion problem were based on simplifications: constant values for transport and thermodynamic properties, flame infinitely thin (infinite fast chemical reaction), no radiative energy loss, no soot formation, no relative velocity with the gas phase, ambient pressure very below the critical value, negligible Soret and Dufort processes. All these asumptions have been changed and more realistic models have been adopted (Faeth, 1977; Law, 1982; Sirignano, 1983; Dwyer, 1989; Givler and Abraham, 1996; Bellan, 2000; Chiu, 2000; Sazhin, 2006). The studies become more and more detailed and describe precisely the droplet combustion problem, but the simulation time becomes longer and longer (Jackson and Avedisian, 1996; Kumar et al., 2002). Fact which forbidens the inclusion of these analyses in numerical spray combustion description. The aim of this work is to present an analytical solution to the droplet combustion problem, whose results may be used in spray combustion numerical codes.

Recently, an analytical solution to the droplet problem was suggested (Fachini, 1999a). The model considered nonunity Lewis number for fuel and oxygen and variable transport coefficients, but a unique constant value for the constant pressure specific heat. The comparison with the experimental results compiled by Puri and Libby (1991) revealed that the vaporization constant is overpredicted but the flame standoff distance is larger by a factor of 2.

The theoretical model suggested by Puri and Libby (1991) is able to predict well the experimental results. They included in the model variable thermodynamical properties and transport coefficient and reaction $CO_2 + H_2 \rightarrow CO + H_2O$. To keep the simplicity of the previous model (Fachini, 1999a), which has an analytical solution, and to incorporate the effects of the constant pressure specific heat on the flame, the previous model is extended considering distinct constant pressure specific heats in each side of the flame.

2. MATHEMATICAL FORMULATION

Formulation for the quasi-steady droplet combustion is presented elsewhere (Fachini, 1999; Fachini et al. 1999). Thus, only essential parts of it will be explicitly presented. The unsteady processes characteritic in the gas phase far from the droplet surface (Waldman, 1975; Crespo and Liñán, 1975; Fachini, 1998; Fachini et al., 1999), the soot formation (Jackson and Avedisian, 1996; Kumar et al., 2002,), multicomponent diffusion effects (Aharon and Shaw, 1997), multicomponent fuels (Fachini et al., 1999) and radiative heat transfer (Fachini et al., 1999) are not considered.

By considering the ambient conditions to be characterised by the temperature T_∞, density ρ_∞, oxygen mass fraction $Y_{O_2\infty}$. The transport coefficients (thermal conductivity and diffusion coefficient) are supposed to depending on temperature, $k/k_\infty = \rho D_i/(\rho_\infty D_{i\infty}) = f(T/T_\infty)$. The constant-pressure specific heat for the gases mixture $\sum_i Y_i c_{pi}$ is variable. The nondimensional quasi-steady conservation equations, describing the gas phase around the droplet with

radius a at time τ ($a \equiv \bar{a}/\bar{a}_0 = 1$ at the time $\tau = 0$), are expressed by

$$x^2 \varrho v = \lambda(\tau) \tag{1}$$

$$\frac{\lambda}{x^2} \frac{\partial}{\partial x} \begin{bmatrix} Le_F y_F \\ Le_O y_O \\ C_p \theta \end{bmatrix} - \frac{1}{x^2} \frac{\partial}{\partial x} (x^2 f \frac{\partial}{\partial x} \begin{bmatrix} y_F \\ y_O \\ \theta \end{bmatrix}) = \dot{\omega}_F \begin{bmatrix} -1 \\ -S \\ Q/Le_F \end{bmatrix} \tag{2}$$

The definition of the nondimensional independent variables are as following: the time $\tau \equiv t/t_c$, and the radial coordinate $x \equiv r/\bar{a}_0$, in which t_c is an estimation of the vaporization time $t_c \equiv \varepsilon(\bar{a}_0^2/\alpha_\infty)$, $\varepsilon \equiv \rho_\infty/\rho_l$ is the ratio of the gas density to the liquid density and $\alpha_\infty \equiv k_\infty/(\rho_\infty c_{p\infty})$ is the thermal diffusivity. The definition of the nondimensional dependent variables (temperature, density, oxygen mass fraction, fuel mass fraction and velocity) are as following: $\theta \equiv T/T_\infty$, $\varrho \equiv \rho/\rho_\infty$, $y_O \equiv Y_{O_2}/Y_{O_2\infty}$, $y_F \equiv Y_F$, and $v \equiv V\bar{a}_0/\alpha_\infty$. The parameters in Eqs. (2) are defined as: Lewis number $Le_i \equiv \alpha_\infty/D_{i\infty}$ ($i = F$ for fuel and $i = O$ for oxidant), $S \equiv Le_O \nu/(Y_{O_2\infty} Le_F)$, note that $s \equiv \nu/Y_{O_2\infty}$ is mass of air to burn stoichiometrically a unit mass of fuel according to the one-step global reaction $F + \nu O_2 \rightarrow (1 + \nu)P$. Heat of combustion Q is defined as $Q \equiv q/(c_{p\infty}T_\infty)$. The nondimensional reaction rates of the fuel oxidation is defined as $\dot{\omega} \equiv \dot{w}(\bar{a}_0^2/\alpha_\infty)Le_F/\rho_\infty$ The parameter C_p is the ratio of an average constant pressure specific heat to the same property determined for the ambient atmosphere condition. Since the average constant pressure specific heat for the gases in the fuel and the oxigen sides are differents, C_p is not the same in the two sides of the flame,

$$C_p \equiv c_p/c_{p\infty} = \begin{cases} C_{pF}, & a \leq x \leq x_f \\ C_{pO}, & x_f \leq x \end{cases}$$

The nondimensional vaporization rate is $\lambda = \dot{m}/(4\pi \bar{a}_0 k_\infty/c_{p\infty})$ and the nondimensional droplet radius, $a = \bar{a}/\bar{a}_0$. According to d^2 law (classical theory), the ratio $\beta \equiv \lambda/a$ is a constant value, known as vaporization constant. β depends on the heat flux to the droplet imposed by the flame.

Equations (2) must be integrated from the droplet surface $x = a$ to the ambient atmosphere $x \rightarrow \infty$. The conditions for these two boundaries are: at $x = a$:

$$\frac{x^2 f}{Le_F} \frac{\partial y_F}{\partial x} = -\lambda(1 - y_{Fs}), \quad x^2 f \frac{\partial \theta}{\partial x} = \lambda L + q^- = \lambda L',$$

$$\theta = \theta_s, \quad y_F = y_{Fs} = exp[\bar{L}(1 - \theta_b/\theta_s)] \tag{3}$$

and for $x \rightarrow \infty$:

$$\theta - 1 = y_O - 1 = y_F = 0 \tag{4}$$

The subscript s represents the droplet surface condition. The nondimensional latent heat L is expressed by $l/(c_p T_\infty)$ and q^- is the heat to inside the droplet. The modified nondimensional latent heat $\bar{L}$ is defined as $\bar{L} = l/RT_b = (L/\theta_b)[\gamma/(\gamma - 1)]$. The definition of the modified latent heat is $L' \equiv L + q'/\lambda$.

In this work, uniform temperature profile is admitted inside the droplet and close to the boiling value, $\theta = \theta_s < \theta_b$ and $q^- \ll 1$. Thereby, the mass conservation equation for the liquid phase leads to

$$\frac{da^2}{d\tau} = -2\frac{\lambda}{a} = -2\beta \tag{5}$$

According to the type of the chemical kinetics adopted, at the flame $x = x_f$, the properties are

$$\theta - \theta_f = y_F = y_0 = 0 \tag{6}$$

The closure for the system of equations is provided by the dimensionless equation of state of the gas, $\varrho\theta = 1$.

The Shvab-Zel'dovich formulation with the excess enthalpy $H \equiv (S+1)Le_F \theta/Q + y_F + y_O$ and the mixture fraction $Z \equiv Sy_F - y_O + 1$ is expressed by (Fachini, 1999; Fachini et al., 1999),

$$\frac{\lambda}{x^2} \frac{\partial}{\partial x} \left(\int_{H(a)}^{H} C_p(H)dH + \int_{Z(a)}^{Z} N(Z)dZ \right) - \frac{1}{x^2} \frac{\partial}{\partial x} \left(x^2 f \frac{\partial H}{\partial x} \right) = 0 \tag{7}$$

$$\frac{\lambda}{x^2} \frac{\partial}{\partial x} \left(\int_{Z(a)}^{Z} Le(Z)dZ \right) - \frac{1}{x^2} \frac{\partial}{\partial x} \left(x^2 f \frac{\partial Z}{\partial x} \right) = 0 \tag{8}$$

in which the Liñán formulation was applied to transform the discontinous constant coefficients to continous ones:

$$C_p(H) = \begin{cases} C_{pF}, & Z > 1 \\ C_{pO}, & Z < 1 \end{cases}, \quad N(Z) = \begin{cases} (Le_F - C_{pF})/S, & Z > 1 \\ (C_{pO} - Le_O), & Z < 1 \end{cases}, \quad Le(Z) = \begin{cases} Le_F, & Z > 1 \\ Le_O, & Z < 1 \end{cases}$$

From the definition of the functions H and Z, the physical variables are defined as following:

$$\theta = \begin{cases} [H - (Z-1)/S]Q/[(S+1)Le_F], & Z > 1 \\ [H + (Z-1)]Q/[(S+1)Le_F], & Z < 1 \end{cases}, \qquad \begin{array}{l} y_F = (Z-1)/S, \quad Z > 1 \\ y_O = (1-Z), \qquad Z < 1 \end{array} \tag{9}$$

The equations for H and Z satisfy the following boundary conditions at the droplet surface $x = a$, which are determined by Eq. (3),

$$H_s \equiv H(a) = \frac{(S+1)Le_F}{Q}\theta_s + y_{Fs}, \quad Z_s \equiv Z(a) = Sy_{Fs} + 1,$$

$$F_{Hs} \equiv \frac{x^2 f}{\lambda}\left.\frac{\partial H}{\partial x}\right|_{x=a} = \frac{(S+1)Le_F}{Q}L' - Le_F(1 - y_{Fs}), \tag{10}$$

$$F_{Zs} \equiv \frac{x^2 f}{\lambda}\left.\frac{\partial Z}{\partial x}\right|_{x=a} = -SLe_F(1 - y_{Fs})$$

from Eq. (6), the conditions at the flame $x = x_f$ are given by

$$H_f \equiv H(x_f) = (S+1)Le_F\theta_f/Q, \quad Z_f \equiv Z(x_f) = 1, \tag{11}$$

and, from Eq. (4), for the ambient atmosphere $x \to \infty$,

$$H_\infty \equiv H(\infty) = (S+1)Le_F/Q + 1, \quad Z_\infty \equiv Z(\infty) = 0, \tag{12}$$

The system of equations (7) to (10) has one eigenvalue: the vaporization constant β ($\equiv \lambda/a$) that is determined by imposing the relation between the fuel mass fraction and temperature at the droplet surface. As part of the solution, the droplet surface temperature θ_s is found.

By integrating Eqs. (7) and (8) with the conditions speficied by Eqs. (9) to (11), from the droplet surface up to a position x, and writing H as a function of Z (flamelet formulation), the following system of equations are found

$$\frac{dH}{dZ} = \left(\int_{H_s}^{H} C_p(H)dH + F_{Hs} + \int_{Z_s}^{Z} N(Z)dZ\right) / \left(\int_{Z_s}^{Z} Le(Z)dZ + F_{Zs}\right) \tag{13}$$

$$-f\frac{\partial Z}{\partial(\lambda/x)} = \int_{Z_s}^{Z} Le(Z)dZ + F_{Zs} \tag{14}$$

From Eq. (14), the mixture fraction Z is a function of the position, $Z = Z(x)$. Since $Z_s > Z(\infty)$ and $\partial Z/\partial x|_a < 0$, then Z decreases monotonically and $x = x(Z)$ is found. The transport coefficient f is a function of the temperature θ and, from Eqs. (9) (13), $\theta = \theta(H(Z), Z)$, thus the system of equations (13) and (14) is well posed and can be integrated.

As can be seen, Eq. (13) can be integrated independently from (14). Once knowing θ_s and the temperature profile $\theta(H(Z), Z) = \theta(Z)$, the value for $Z(a)$ is specified and Eq. (14) is solved with the imposition of two boundary conditions: $Z(x = a) = Sy_{Fs} + 1$ and $Z(x \to \infty) = 0$. The eigenvalue $\beta \equiv \lambda/a$ is found.

Equation (13) has analytical solution. In the present analysis, the system of equations (13) and (14) are employed to describe the droplet combustion problem. The integral terms in these equationas are

$$\int_{H_s}^{H} C_p(H)dH = \begin{cases} C_{pF}(H - H_s), & 1 \leq Z \leq Z_s \\ C_{pF}(H_f - H_s) + C_{pO}(H - H_f), & 0 \leq Z \leq 1 \end{cases} \tag{15}$$

$$\int_{Z_s}^{Z} N(Z)dZ = \begin{cases} (Le_F - C_{pF})(Z - Z_s)/S, & 1 \leq Z \leq Z_s \\ (Le_F - C_{pF})(1 - Z_s)/S + (C_{pO} - Le_O)(Z - 1), & 0 \leq Z \leq 1 \end{cases} \tag{16}$$

$$\int_{Z_s}^{Z} Le(Z)dZ = \begin{cases} Le_F(Z - Z_s), & 1 \leq Z \leq Z_s \\ Le_F(1 - Z_s) + Le_O(Z - 1), & 0 \leq Z \leq 1 \end{cases} \tag{17}$$

Equation (13) are speficied for the fuel side of the flame ($Z > 1$) and for the oxiygen side ($Z < 1$). It can be written as

$$\frac{d(H - H_i)}{d(Z_i - Z)} = \frac{C_p(H - H_i) - N(Z_i - Z)}{Le(Z_i - Z)} \tag{18}$$

in which

$$H_i = \begin{cases} 1 + [(S+1)Le_F/Q](C_{pF}\theta_s - L)/C_{pF}, & (i=1)\ Z \geq 1 \\ ([(S+1)Le_F/Q][(C_{pO} - C_{pF})\theta_f + C_{pF}\theta_s - L + Q]/C_{pO} - s, & (i=2)\ Z \leq 1 \end{cases}$$

$$Z_i = \begin{cases} S+1, & (i=1)\ Z \geq 1 \\ s+1, & (i=2)\ Z \leq 1 \end{cases} \tag{19}$$

The solution of Eq. (18) is (Fachini, 1999a)

$$H - H_i = -\frac{N}{Le - C_p}(Z_i - Z) + G_i(Z_i - Z)^{C_p/Le} \tag{20}$$

Applying the condition at the ambient atmosphere specified in Eq. (11) in Eq. (20) for the domain $Z \leq 1$, the value of the integration constant for the oxygen fuel side $G_i = G_2$ (for $Z < 1$) is determined

$$G_2 = -\frac{1}{(s+1)^{C_{pO}/Le_O}}\frac{1}{C_{pO}}\frac{(S+1)Le_F}{Q}\left[(C_{pO} - C_{pF})\theta_f + C_{pF}\theta_s - L + Q - C_{pO}\right]$$

In the same way, applying the condition at the droplet surface ($Z = Z_s$) on the function H, the integration constant $G_i = G_1$ for Eq. (20) in the fuel side ($Z > 1$) is found

$$G_1 = \frac{(S+1)Le_F}{Q}\frac{L/C_{pF}}{[S(1-y_{Fs})]^{C_{pF}/Le_F}}$$

The flame temperature can be calculated by any expression from Eq. (20). For compactness, the condition Eq. (11) is applied to (20) in the oxygen side of the flame ($Z < 1$),

$$\theta_f = \frac{C_{pO} + (C_{pF}\theta_s - L + Q - C_{pO})\left\{1 - [s/(1+s)]^{C_{pO}/Le_O}\right\}}{C_{pF} + (C_{pO} - C_{pF})[s/(1+s)]^{C_{pO}/Le_O}} \tag{21}$$

The continuity condition of the function H permits the determination an expression that relates the fuel mass fraction and the temperature at the droplet surface ($Z = Z_s$). Therefore, imposing this condition on Eq. (20), the following expression is found for the fuel mass fraction at the droplet surface y_{Fs}

$$\frac{L/C_{pF}}{(1-y_{Fs})^{C_{pF}/Le_F}} = \left(\frac{C_{pO} - C_{pF}}{C_{pO}}\right)\left(\theta_f - \theta_s + \frac{Q}{C_{pO} - C_{pF}} + \frac{L}{C_{pF}}\right) -$$

$$\left(\frac{s}{s+1}\right)^{C_{pO}/Le_O}\left[\left(\frac{C_{pO} - C_{pF}}{C_{pO}}\right)\theta_f + \frac{C_{pF}}{C_{pO}}\theta_s - \frac{L}{C_{pO}} + \frac{Q}{C_{pO}} - 1\right] \tag{22}$$

The solution of Eq. (22) together with the Clausius-Clapeyron relation, Eq. (3), determines the droplet surface temperature θ_s and fuel mass fraction on the droplet surface y_{Fs} However, if the approximation $\theta_s = \theta_B$ is applied, Eq. (22) determines directly the value of y_{Fs}.

The determination of the other droplet combustion properties, the constant of vaporization β and the flame standoff distance x_f/a, is achived by the integration of Eq. (14). To perform that task is necessary to know the dependence of the transport coefficients f and the temperature as a function of the mixture fraction Z. In this work, $f = \theta^n$ is chosen ($n = 0.5$). From Eqs. (9) and (20), the temperature as a function of Z is

$$\theta = \theta_s - \frac{L}{C_{pF}}\left[1 - \left(\frac{Z_1 - Z}{S(1-y_{Fs})}\right)^{C_{pF}/Le_F}\right] \tag{23}$$

for $Z \geq 1$ and

$$\theta = 1 + \left(\frac{C_{pO} - C_{pF}}{C_{pO}}\theta_f + \frac{C_{pF}}{C_{pO}}\theta_s + \frac{Q}{C_{pO}} - \frac{L}{C_{pO}} - 1\right)\left[1 - \left(\frac{Z_2 - Z}{1+s}\right)^{C_{pO}/Le_O}\right] \tag{24}$$

for $Z \leq 1$. Therefore, by integrating Eq. (14) in the domains $Z > 1$ and $Z < 1$, one finds

$$\beta\left(1 - \frac{a}{x_f}\right) = \int_1^{1/(1-y_{Fs})}\frac{\{A_1 + B_1[1 - \tilde{Z}^{C_{pF}/Le_F}]\}^n d\tilde{Z}}{Le_F\tilde{Z}} \tag{25}$$

$$\beta\frac{a}{x_f} = \int_{s/(s+1)}^1\frac{\{A_2 + B_2[1 - \bar{Z}^{C_{pO}/Le_O}]\}^n d\bar{Z}}{Le_O\bar{Z}} \tag{26}$$
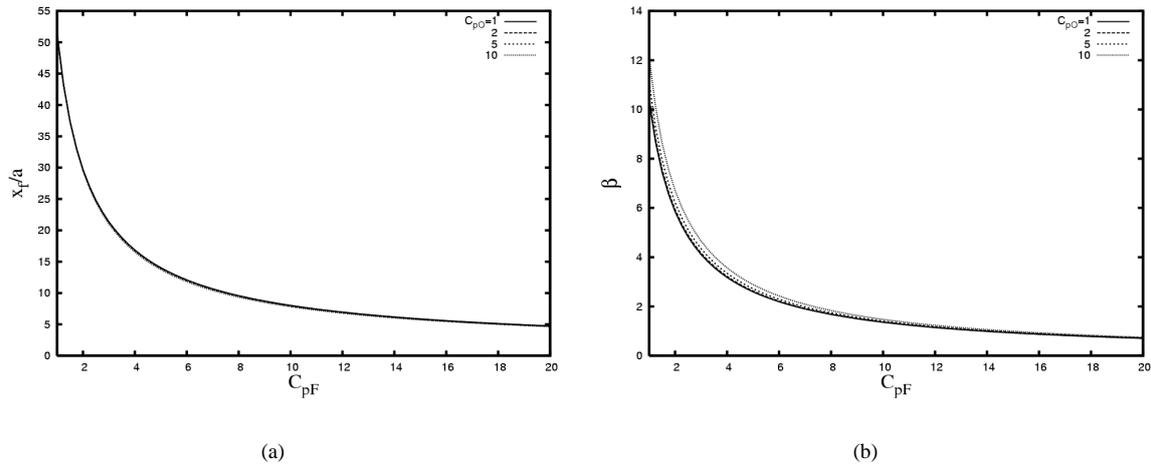
(a)

(b)

Figure 1. (a) Flame standoff distance x_f/a and (b) vaporization constant β as a function of the C_{pF} for four values of C_{pO}.
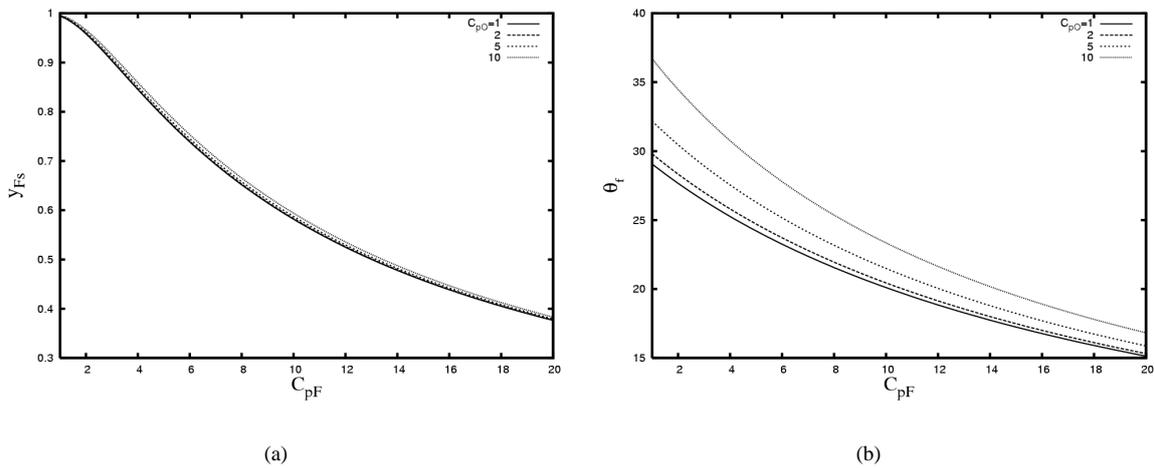

(a)

(b)

Figure 2. (a) Fuel mass fraction at the droplet surface y_{Fs} and (b) flame temperature constant θ_f as a function of the C_{pF} for four values of C_{pO}.

in which $\tilde{Z} \equiv (Z_1 - Z)/[S(1 - y_{Fs})]$, $\bar{Z} \equiv (Z_2 - Z)/(s + 1)$ and the constants A_i and B_i are

$$A_i = \begin{cases} \theta_s, & Z \geq 1 \ (i = 1) \\ 1, & Z \leq 1 \ (i = 2) \end{cases},$$

and

$$B_i = \begin{cases} -L/C_{pF}, & Z \geq 1 \ (i = 1) \\ [(C_{pO} - C_{pF})\theta_f + C_{pF}\theta_s + Q - L - C_{pO}]/C_{pO}, & Z \leq 1 \ (i = 2) \end{cases}$$

3. COMMENTS AND CONCLUSION

In order to include a droplet combustion model (sub-grid model) in a spray combustion simulation, the model must represents well the physics and be computationally economic. The aim is to find analytical expressions for the sub-grid model which represent pratically no cost in the integration time. Based on that, it is presented a droplet combustion model in which are considered the transport coefficients variable, nonunity Lewis numbers and different constant value for the constant pressure specific heat in each side of the flame. This model with two ajusting parameters, C_{pF} and C_{pO}, permits the experimental results to be better represented by the theoretical results. Because C_{pF} can be about 5 to 10, a first analysis points out that it has a strong influence on all droplet combustion properties: vaporization rate β, standoff distance x_f/a, fuel mass fraction y_{Fs} and the flame temperatura θ_f. However, since C_{pO} is about 2, it is expected that

its influence is not significant on all droplet combustion properties, but this is not observed in the results. The importance of this model is on the analytical expression for the problem unkowns: vaporization rate, flame standoff distance, flame temperature. This model is a extension of the previous one (Fachini, 1999a). Figures 1 and 2 present the results of the suggested model.

The classic results, $C_{pO} = C_{pF} = Le_O = Le_F = 1$ and $n = 0$, the standoff distance x_f/a is overpredicted. The models which consider the constant pressure specific heat variable with temperature and composition are able to predict well x_f/a. Based on this result, the present model was elaborated joining the possibility to solve analytically and to reproduce the experimental results. Figure 1.a shows the dependence of the standoff distance x_f/a on the constant pressure specific heat C_{pF} for the fuel side of the flame. For $C_{pF} \sim 10$, $x_f/a \sim 10$ is a well predicted value compared with results from detailed model $x_f/a = 9.8$ (Puri and Libby, 1991), which are not in good agreement with experimental results $x_f/a \sim 7$ (Kumagai et al., 1971).

Figure 1.b exhibits the variation of the vaporization constant β with the constant pressure specific heat C_{pF}. As observed for x_f/a, the vaporization constant β has a strong dependence on C_{pF}. Also, the model is able to reproduce well the experimental results.

Although the success on predicting these two droplet combustion properties, the present model fails in predicting the fuel mass fraction at the droplet surface y_{Fs}, as seen in Fig. 2.a. The reson for that is not understood, a further analysis is necessary explain this failure.

The increasing of C_{pF} makes the droplet combustion properties to deacrese, an expected results. However, the increasing of C_{pO} leads to the increase of the flame temperature θ_f, as seen in Fig. 2.b. An carefull analysis of Eq. (21) shows that the choice of the value for C_{pO} modifies the thermodynamic gas properties out of the flame as well as the transport properties by the term C_{pO}/Le_O. It is worth to note that $C_{pO}/Le_O = D_O/(k_\infty/\rho_\infty c_{pO}) = 1/Le_{O\ effective}$. Then, by doubling the value of C_{pO}, for exemple, twice more energy is stored in molecule internal energy modes, which leads to decreasing the gas temperature, including the flame temperature. In the other hand, the increase of C_{pO} makes a proportional reduction in the gases thermal diffusivity, which favors the mass diffusivity. The consequence of this is an increase of the gas temperature because of the oxidant transport velocity to the flame is larger than the heat transport velocity from the flame. The result depicted in Fig. 2.b demonstrates that the transport effect produced by the differents values of C_{pO} dominates the thermodynamics effect.

4. CONCLUSION

The present model is able to reproduce well the experimental results concerning the flame standoff distance x_f/a. However, it does not predict well other droplet combustion properties.

5. ACKNOWLEDGEMENTS

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