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2007

MIMS EPrint: **2007.142**

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ISSN 1749-9097

# **ANALYSIS OF A LAMINAR PREMIXED SPRAY FLAME WITH MODIFIED ZELDOVITCH-LINAN KINETICS**

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## **ABSTRACT**

A new preliminary analysis of a one dimensional laminar lean premixed spray flame has been performed using a chain branching/chain breaking chemical kinetic scheme and under the assumption that the fuel droplets evaporate in a sharp front. The sensitivity of the flame speed and the location of the evaporation front to the initial droplet load have been demonstrated. A linear stability analysis reveals the way in which the spray's presence modifies the neutral stability curves.

## INTRODUCTION

The one-dimensional laminar premixed *gas* flame has served as a cornerstone in the field of combustion being a relatively simple paradigm for capturing the subtle way in which physico-chemical mechanisms interact under a wide variety of operating circumstances in premixed combustion systems. As spray combustion plays such an important role in many aerospace (and other) practical applications it is not surprising that premixed laminar *spray* flames have also been the subject of theoretical/numerical and experimental studies. Experimental studies [1-9] have revealed the fact that the very presence of a spray of droplets in the unburned premixture can have a profound impact on the structure, the speed and the stability of the flames they are fueling. An in-depth discussion of the pertinent literature and the somewhat sparse theoretical analyses (see, e.g. [10-12]) can be found in Greenberg et al.[13]. In keeping with parallel theoretical studies of laminar gas flames the role of the detailed flame chemistry in spray flames was encompassed within a single global kinetic scheme that ensures that the correct balance between mass or heat convection and diffusion and exothermic chemical reaction was retained in a satisfactory fashion. However, the success of one-step chemical kinetic models is overshadowed by the fact that the role of intermediate chemical reactants is completely absent, even from ignition studies (see, eg. [14]) where chain branching is of utmost importance for determining whether combustion will actually occur or not.

A moderate more realistic extension of the single step chemistry model is based on considering the prime importance of elementary chain branching reactions in controlling the multiple chemical step-ways that make up a full kinetic description. These chain branching steps involve radical and/or atoms that break down the fuel and/or oxidant thereby producing a radical pool. Ultimately, radicals are also involved in chain breaking/recombination steps that lead to the appearance of products of reaction.

Zeldovitch et al. [15] were the first to model purely gaseous premixed flames with a chain mechanism using a two-step chemical mechanism. Other work followed using this non-linear mechanism (see, for example, Joulin et al. [16]) or, more recently, a modified mechanism by Dold et al.[17-19]. The advantage of the latter mechanism is the fact that it takes the chain breaking or completion step to be linear in the concentration of some intermediate radical or species. This is completely consistent with the final state being an equilibrium one in a broader chemical system and bears the added advantage of enabling mathematical tractability.

In the current work we explore a new model of a one-dimensional laminar spray flame in which a fuel spray evaporates in a sharp front upstream of the flame front. We adopt Dold's modified Zeldovitch-Linan kinetics to describe the chemical kinetics of the flame front in a more general manner than has been hitherto carried out in the spray flame context. In addition, we investigate the way in which the presence of the spray influences the flame front stability.

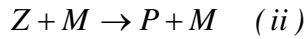
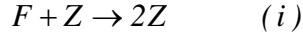
## GOVERNING EQUATIONS

Consider a one-dimensional planar laminar flame front propagating through a fresh homogeneous mixture of fuel vapor, fuel droplets and air. The droplets are viewed from a far-field vantage point, i.e. their average velocity is equal to that of their host environment. For qualitative purposes this approach has been demonstrated to be quite valid [20]. The droplets in the spray evaporate in a sharp front that is located at the point where the temperature is that of the boiling point of the liquid fuel,  $T_d$ . The temperature

of the droplets is taken as equal to that of the surroundings; essentially the droplets heat-up time is small compared to the characteristic time associated with their motion.

It is assumed that the various transport coefficients such as thermal conductivity, diffusion coefficients, specific heat at constant temperature, latent heat of vaporization of the liquid droplets etc. can be satisfactorily specified by representative constant values. Furthermore, the transport properties will be supposed to be determined primarily by the properties of the gaseous species. This follows from the implicit assumption that the liquid fuel volume fraction is sufficiently small.

The modified Zeldovitch-Linan chemical reaction scheme suggested by Dold et al.[17-19] is adopted here, viz.



where  $F$  denotes the fuel vapor,  $Z$  the intermediate product,  $P$  the product of reaction and  $M$  any molecule that triggers the conversion of the intermediate to the product. Reaction (i) is a high activation energy chain branching reaction whereas reaction (ii) is the chain terminating step that is thermally neutral but which provides the dominant exothermal contribution to the heat balance. Typical data for hydrocarbon chemistry readily verifies these assertions. In the current analysis only a fuel lean system is considered.

Since the velocity of propagation of the flame is much less than the velocity of sound, dynamic compressibility effects in the mixture can be neglected. Thus, the density becomes a function of the temperature through the gas law.

The governing equations for the situation at hand take the following form

$$Le_F (F_t + SF_x) = \nabla^2 F - \beta^2 FZk(T) + Le_F V \quad (1)$$

$$Le_Z (Z_t + SZ_x) = \nabla^2 Z + \beta^2 FZk(T) - Z \quad (2)$$

$$T_t + ST_x = \nabla^2 T + QZ / Le_F - LV - aT \quad (3)$$

$$D_t + SD_x = -V \quad (4)$$

with

$$k(T) = \exp(\beta(T-1)/(1+\alpha(T-1))) \quad (5)$$

The general background underlying the form of these equations and the way in which the variables have been normalized appears in Dold et al [19] to which the interested reader is referred. Eq.(1) is the conservation equation for the fuel vapor mass fraction,  $F$ ,  $Le_F$  is the fuel vapor's Lewis number,  $S$  is the planar flame speed,  $\beta$  is the high activation energy of the chain branching reaction,  $k(T)$  is the exponential part of the Arrhenius term for the reaction rate of reaction (i) and  $V$  is the rate of evaporation of fuel droplets. Eq(2) describes the conservation of the intermediate species mass fraction  $Z$  with  $Le_Z$  being the relevant Lewis number. Note the third term on the RHS of this equation represents the removal of the intermediate via reaction (ii). Eq.(3) is the energy conservation equation. On the RHS the second term relates to the exothermic reaction (ii), the third term to the heat loss incurred by droplet evaporation ( $L$  is associated with the latent heat of vaporization of the liquid fuel) and the fourth term to linear heat loss, with constant  $a > 0$ . Eq.(4) describes the conservation of liquid fuel in the spray of droplets.

The boundary conditions for a flame traveling from right to left are

$$\lim_{x \rightarrow -\infty} (F, Z, T, D) = (1 - \delta, 0, 0, \delta) \quad (6)$$

$$\lim_{x \rightarrow \infty} (F, Z, T, D) = (0, 0, T_b, 0) \quad (7)$$

Here  $\delta$  is called the initial droplet load. It represents the ratio of the mass fraction of liquid fuel to that of the total fuel (i.e. fuel liquid + vapor). We shall take the total fuel mass fraction to be constant so that different values of  $\delta$  correspond to different combinations of the initial liquid and vapor mass fractions. The temperature  $T_b$  will be equal to zero in the non-adiabatic case  $a > 0$ . If  $a = 0$  it is not hard to show that  $T_b = Q - L\delta$ .

Taking the branching reaction to occur at a sheet,  $x = 0$ , the relevant reaction term in the Eqs(1) and (2) is negligible for  $x \neq 0$ . In addition, since the droplets are taken to evaporate in a front, say at  $x = d$ , the relevant evaporation related terms can be erased when  $x \neq d$ . Thus, the reduced equations for the laminar planar spray flame are simply

$$Le_F (F_t + SF_x) = \nabla^2 F \quad (8)$$

$$Le_Z (Z_t + SZ_x) = \nabla^2 Z - Z \quad (9)$$

$$T_t + ST_x = \nabla^2 T + QZ / Le_F - aT \quad (10)$$

$$D_t + SD_x = 0 \quad (11)$$

with conditions across the evaporation front

$$[F_n] = -S_d Le_F \delta, [T_n] = S_d L \delta, [D] = -\delta, [F] = [Z] = [Z_n] = 0, T = T_d \quad (12)$$

in which  $S_d$  is the normal propagation speed of the evaporation front, and conditions across the branching reaction sheet ( $\beta \gg 1$ )

$$[F_n] + [Z_n] = [T_n] = [F] = [Z] = 0, T = 1 \quad (13)$$

In these conditions the subscript  $n$  denotes the derivative in the normal direction.

### STEADY STATE SOLUTION

For the steady state solution depending only on  $x$  (with  $\partial_t = \partial_y = \partial_z = 0$ ) and with  $S_d = S$  and evaporation at  $x = d_0$  the solutions of the governing equations can readily be determined.

In the region  $-\infty < x \leq d_0$

$$D = D_0(x) = \delta \quad (14a)$$

$$Z = Z_0(x) = \frac{Le_F S}{\gamma_1 + \gamma_2} e^{\gamma_1 x} \quad (14b)$$

$$F = F_0(x) = 1 - \delta - (1 - \delta e^{-Le_F S d_0}) e^{Le_F S x} \quad (14c)$$

$$T = T_0(x) = (T_d + G_1 e^{\gamma_1 d_0}) e^{\mu_1 (x - d_0)} - G_1 e^{\gamma_1 x} \quad (14d)$$

In the region  $d_0 \leq x \leq 0$

$$D = D_0(x) = 0 \quad (15a)$$

$$Z = Z_0(x) = \frac{Le_F S}{\gamma_1 + \gamma_2} e^{\gamma_1 x} \quad (15b)$$

$$F = F_0(x) = 1 - Le_F e^{Le_F S x} \quad (15c)$$

$$T = T_0(x) = (1 + G_1) e^{-\mu_2 x} + H(e^{\mu_1 x} - e^{-\mu_2 x}) - G_1 e^{\gamma_1 x} \quad (15d)$$

and in  $0 \leq x < \infty$

$$D = D_0(x) = 0 \quad (16a)$$

$$Z = Z_0(x) = \frac{Le_F S}{\gamma_1 + \gamma_2} e^{-\gamma_2 x} \quad (16b)$$

$$F = F_0(x) = 0 \quad (16c)$$

$$T = T_0(x) = (1 + G_2) e^{-\mu_2 x} - G_2 e^{-\gamma_2 x} \quad (16d)$$

In these solutions

$$\gamma_{1,2} = \frac{1}{2} \left( \sqrt{(Le_F S)^2 + 4} \pm Le_Z S \right), \quad \mu_{1,2} = \frac{1}{2} \left( \sqrt{S^2 + 4a} \pm S \right) \quad (17a)$$

$$G_1 = \frac{QS}{(\gamma_1 + \gamma_2)(\gamma_1 - \mu_1)(\gamma_1 + \mu_2)}, \quad G_2 = \frac{QS}{(\gamma_1 + \gamma_2)(\gamma_2 - \mu_2)(\gamma_2 + \mu_1)} \quad (17b)$$

$$H(e^{\mu_1 d_0} - e^{-\mu_2 d_0}) = T_d - (1 + G_1) e^{-\mu_2 d_0} + G_1 e^{\gamma_1 d_0} \quad (17c)$$

Applying the jump conditions  $[T_x] = SL\delta$  at the evaporation front and  $[T_x] = 0$  at the branching reaction front leads to the following set of two nonlinear algebraic equations to be solved for the evaporation front location and the flame speed, given the values of  $Le_F, Le_Z, Q, \delta, T_d, a$ :

$$G_1 (\mu_1 e^{\gamma_1 d_0} + \mu_2 e^{-\mu_2 d_0}) + \mu_2 e^{-\mu_2 d_0} + \mu_1 T_d = H(\mu_1 e^{\mu_1 d_0} + \mu_2 e^{-\mu_2 d_0}) - SL\delta \quad (18)$$

$$G_1 (\gamma_1 + \mu_2) + G_2 (\gamma_2 - \mu_2) = H(\mu_1 + \mu_2) \quad (19)$$

It is interesting to note that although the shape of  $F_0(x)$  and the magnitude of  $Z_0(x)$  depend on  $Le_F$  Eqs (17)-(19) do not.

## RESULTS - STEADY STATE SOLUTION

In Figure 1 we present flame speeds and the location of the evaporation front as a function of the heat loss parameter for different initial droplet loads. The Lewis number of the intermediate species has been taken as unity – in practice it is not likely to be beyond the close proximity of one. Since maximum temperatures rarely exceed 2500K taking the unburned temperature to be about 300K and the branching temperature to be about 1400K suggests that the realistic values of  $Q$  are likely to be in the vicinity of two. Not unexpectedly the maximum permitted value of the heat loss parameter grows as the initial droplet load decreases. The case  $\delta = 0$  corresponds to the single phase gas problem when no droplets are present in the initial unburned mixture. The reduction of the maximum heat loss parameter as the droplet load increases is due to the increased additional heat loss resulting from the evaporation of the droplets. Not unsurprisingly, this general behavior of the flame speed with heat loss concurs with analyses using a single global chemical reaction [21]. Note, also, that the location of the evaporation front moves away from the branching reaction front as the droplet load increases.

For Figure 2 the influence of the exothermic heat of reaction is illustrated for a droplet load of one. The maximum permitted value of the heat parameter grows as  $Q$  increases as do the values of the flame speed. Of course, the heat loss effect of the liquid fuel exhibits

itself inasmuch as the equivalent flame speeds curves with no initial liquid fuel (not shown here) are displaced to the right. It is interesting to note that the evaporation front location decreases as  $Q$  increases.

### LINEAR STABILITY ANALYSIS

For small amplitude disturbances with a wave-number  $k$  and a growth rate  $\lambda$  linear stability can be examined by assuming that the branching reaction interface behaves like  $x = e^{\lambda t + iky}$  with  $|e^{\lambda t + iky}| \ll 1$ . The accompanying perturbations in  $F, Z, T, d$  and  $S_d$  are taken to have the form

$$(F, Z, T, d, S_d) \approx (F_0, Z_0, T_0, d_0, S) + (F_1(x), Z_1(x), T_1(x), d_1, -\lambda d_1) e^{\lambda t + iky} \quad (20)$$

Substituting in the governing equations (8)-(11) and the matching equations (12) and (13) and making use of the steady state solutions leads to the following equations

$$F_1'' - Le_F S F_1' - (Le_F \lambda + k^2) F_1 = 0 \quad (21)$$

$$Z_1'' - Le_Z S Z_1' - (Le_Z \lambda + k^2 + 1) Z_1 = 0 \quad (22)$$

$$T_1'' - S T_1' - (\lambda + k^2 + a) T_1 = -Q Z_1 / Le_F \quad (23)$$

$$S D_1' + \lambda D_1 = 0 \quad (24)$$

in which it can be assumed that  $F_1 \equiv 0$  for  $x > 0$  and  $D_1 \equiv 0$  for  $x > d$ . The appropriate boundary conditions at infinity are

$$\lim_{x \rightarrow -\infty} (F_1, Z_1, T_1, D_1) = (0, 0, 0, 0) \quad (25)$$

$$\lim_{x \rightarrow \infty} (Z_1, T_1) = (0, 0) \quad (26)$$

and the matching conditions at the evaporation front become

$$\left[ F_1' \right] = Le_F \delta d_1 (\lambda + Le_F S^2), \left[ T_1' \right] = -L \delta d_1 \lambda - d_1 \left[ T_0'' \right], \left[ Z_1 \right] = \left[ Z_1' \right] = 0 \quad (27a)$$

$$\left[ F_1 \right] = Le_F S \delta d_1, \left[ T_1 \right] = -L S \delta d_1, T_1^- = -d_1 (\mu_1 T_d + e^{\gamma_1 d_0} (\mu_1 - \gamma_1) G_1) \quad (27b)$$

whereas those at the reaction front are

$$\left[ F_1' \right] + \left[ Z_1' \right] = (Le_Z - Le_F) Le_F S^2, \left[ T_1' \right] = 0 \quad (28a)$$

$$\left[ F_1 \right] = -Le_F S, \left[ Z_1 \right] = Le_F S, T_1 = \mu_2 - G_2 (\gamma_2 - \mu_2) \quad (28b)$$

The solution of these equations subject to the boundary and matching conditions leads to the following two nonlinear algebraic equations from which the growth rate  $\lambda$  and  $d_1$  can be determined as functions of the wave-number and the other parameters of the problem

$$\frac{PQ}{Le_F} \left( \frac{1}{\mu_4 + \gamma_3} + \frac{1}{\mu_3 + \gamma_4} \right) + \frac{QS}{\mu_3 + \gamma_4} + (\mu_3 + \mu_4) \left( \frac{QS}{(\gamma_1 + \gamma_2)(\gamma_2 + \mu_1)} + M_2 - \mu_2 \right) = 0 \quad (29a)$$

$$L \delta d_1 (\lambda + S(\mu_1 - \mu_3)) - M_2 (\mu_3 + \mu_4) e^{-\mu_4 d_0} + e^{-\mu_2 d_0} \mu_2 (\mu_1 + \mu_2) d_1 (G_1 - H + I) = 0 \quad (29b)$$

In these equations

$$P = \frac{1}{(\gamma_3 + \gamma_4)} \left( R(v_1 + v_2) e^{v_2 d_0} - Le_F S (v_1 + \gamma_4) + (Le_F - Le_Z) Le_F S^2 \right) \quad (30a)$$

$$\nu_{1,2} = \frac{1}{2} \left( \sqrt{4(Le_F \lambda + k^2) + Le_F^2 S^2} \pm Le_F S \right) \quad (30b)$$

$$\gamma_{3,4} = \frac{1}{2} \left( \sqrt{4(Le_Z \lambda + k^2 + 1) + (Le_Z S)^2} \pm Le_Z S \right) \quad (30c)$$

$$\mu_{3,4} = \frac{1}{2} \left( \sqrt{4(\lambda + k^2 + a) + S^2} \pm S \right) \quad (30d)$$

$$R = \frac{1}{(\nu_1 + \nu_2)} (\nu_1 S - \lambda - Le_F S^2) Le_F \delta d_1 \quad (30e)$$

$$M_2 (e^{-\mu_4 d_0} - e^{\mu_3 d_0}) = -SL \delta d_1 + (K_1 + M_1 + G_2 (\gamma_2 - \mu_2) - \mu_2) e^{\mu_3 d_0} \quad (30f)$$

$$M_1 = -K_1 e^{d_0(\gamma_3 - \mu_3)} - d_1 e^{-\mu_3 d_0} (\mu_1 T_d + G_1 e^{\gamma_1 d_0} (\mu_1 - \gamma_1)) \quad (30g)$$

$$K_1 = \frac{PQ}{Le_F (\mu_3 - \gamma_3) (\mu_4 + \gamma_3)} \quad (30h)$$

## RESULTS – STABILITY ANALYSIS

Given a steady state solution with flame speed and evaporation front location satisfying Eqs (18) and (19) the dispersion relations (29a) and (29b) can be solved numerically to find the dependence of the least stable growth rate  $\lambda$  on the wave-number  $k$ . We show typical results for  $Le_F < 1$  and for various initial droplet loads. For  $Le_F < 1$  the least stable root appears to be real. It is always zero for  $k=0$  but elsewhere it varies with  $k$ . For non-zero wave numbers it first becomes positive as  $Le_F$  decreases through a threshold value. For the adiabatic case,  $a=0$ , the neutral stability curves are drawn in Figure 3. For conditions above any given curve the flame will be stable whereas for conditions below the curve the flame will develop cellular instability. It is interesting to observe that for this lean fuel case the presence of the spray appears to enhance stability. This is qualitatively similar to what was found in [13] for a finite rate of evaporation, using an NEF analysis with a single step global chemical model. However, the effect of the spray is far more pronounced in the current work.

In Figure 4 the neutral stability curves are plotted for a higher value of the latent heat of vaporization,  $L$ . The sensitivity of the curves to the value of  $L$  is rather dramatic. It can be seen that for  $\delta = 0.65$  the curve transcends that of the purely gaseous flame and a small region exists in which a cellular flame will be observed even though an equivalent gaseous flame will be stable.

## CONCLUSIONS

A new preliminary analysis of a one dimensional laminar lean premixed spray flame has been performed using a chain branching/chain breaking chemical kinetic scheme and under the assumption that the fuel droplets evaporate in a sharp front. The sensitivity of the flame speed and the location of the evaporation front to the initial droplet load have been demonstrated. A linear stability analysis reveals the way in which the spray's presence modifies the neutral stability curves. In practical circumstances the Lewis number of hydrocarbon fuels will be greater than unity. In such instances pulsating instability was observed by Atzler[9] for fuel lean flames. For fuel rich flames only cellular instability was found. Extension of the current work is in process to determine how the chain branching/breaking mechanism and the spray of fuel droplets (a) influences the pulsating mode of instability, and (b) alters the onset of cellular stability.

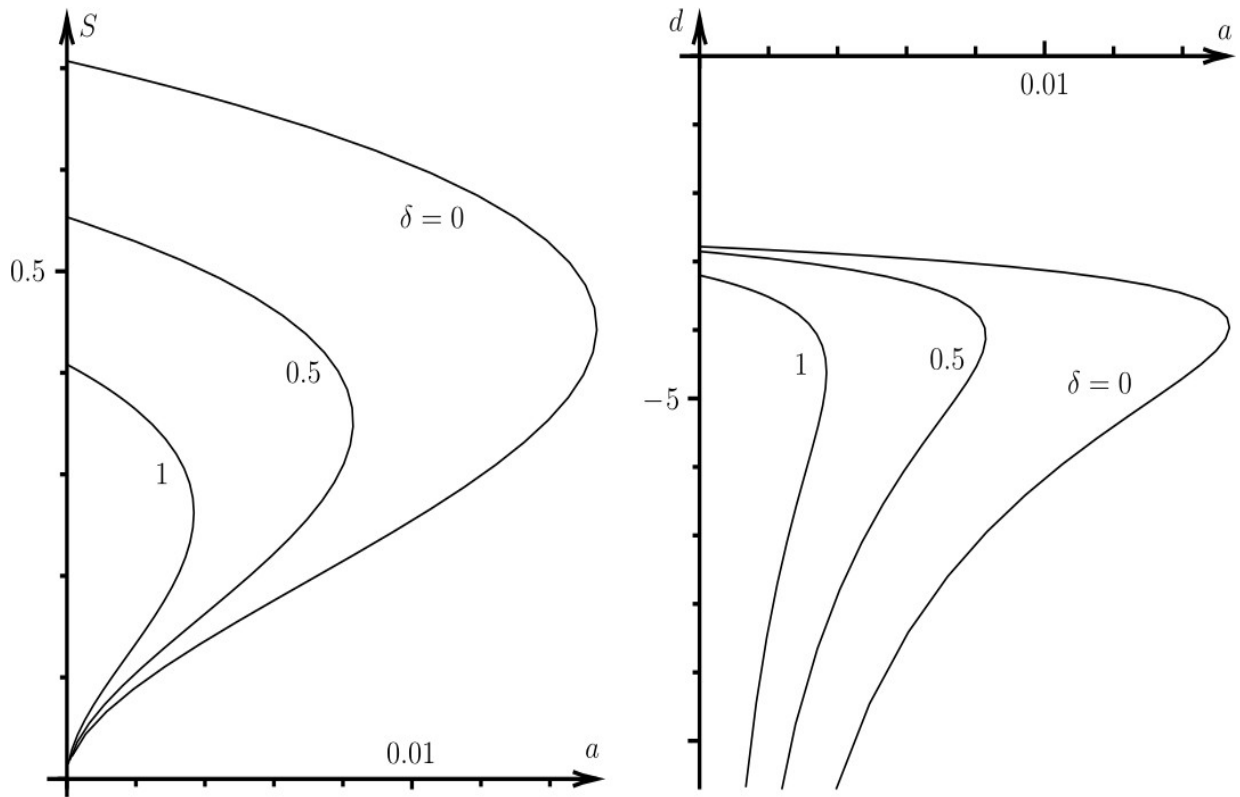


## ACKNOWLEDGEMENTS

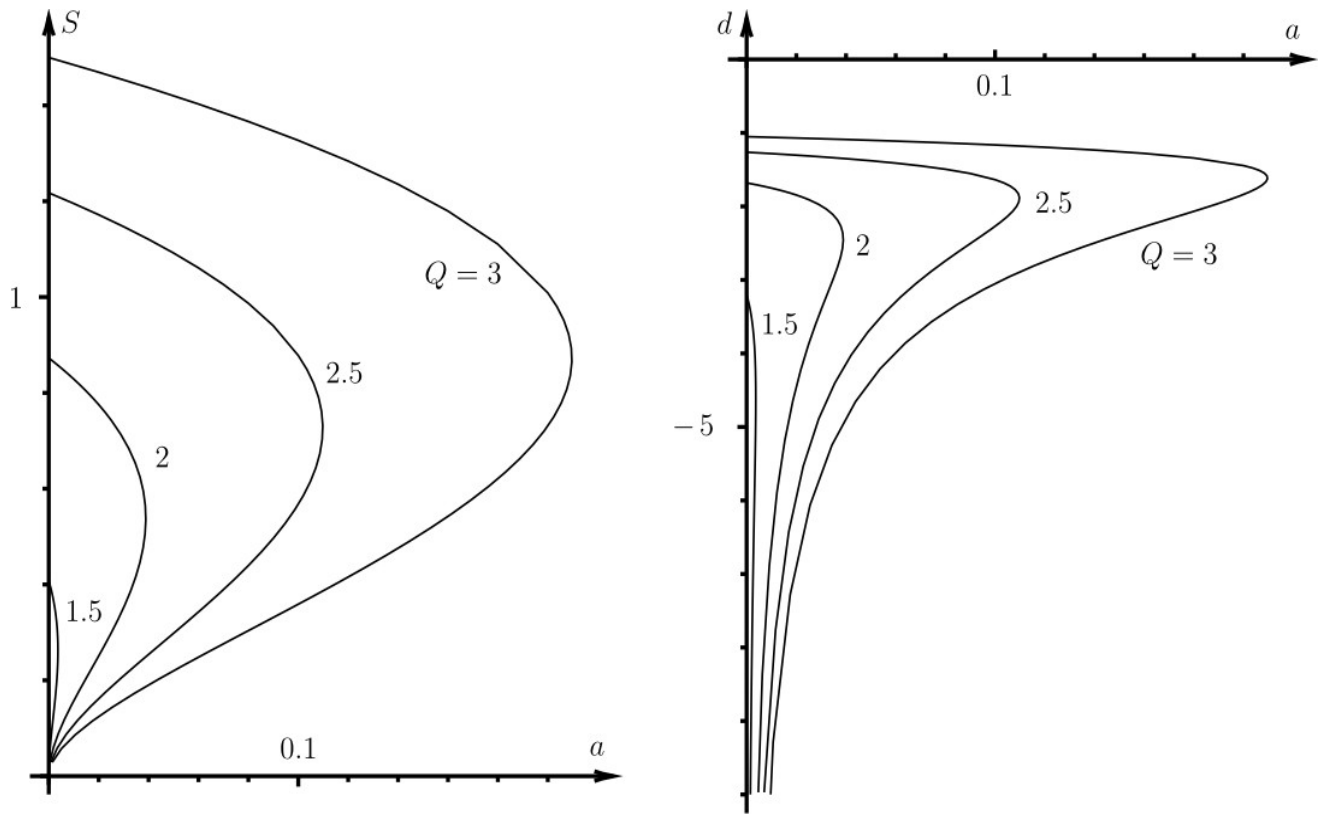
J.B.G. acknowledges the partial support of the Technion Fund for Promotion of Research and a grant from the US-Israel Bi-National Science Foundation (2004069).

## REFERENCES

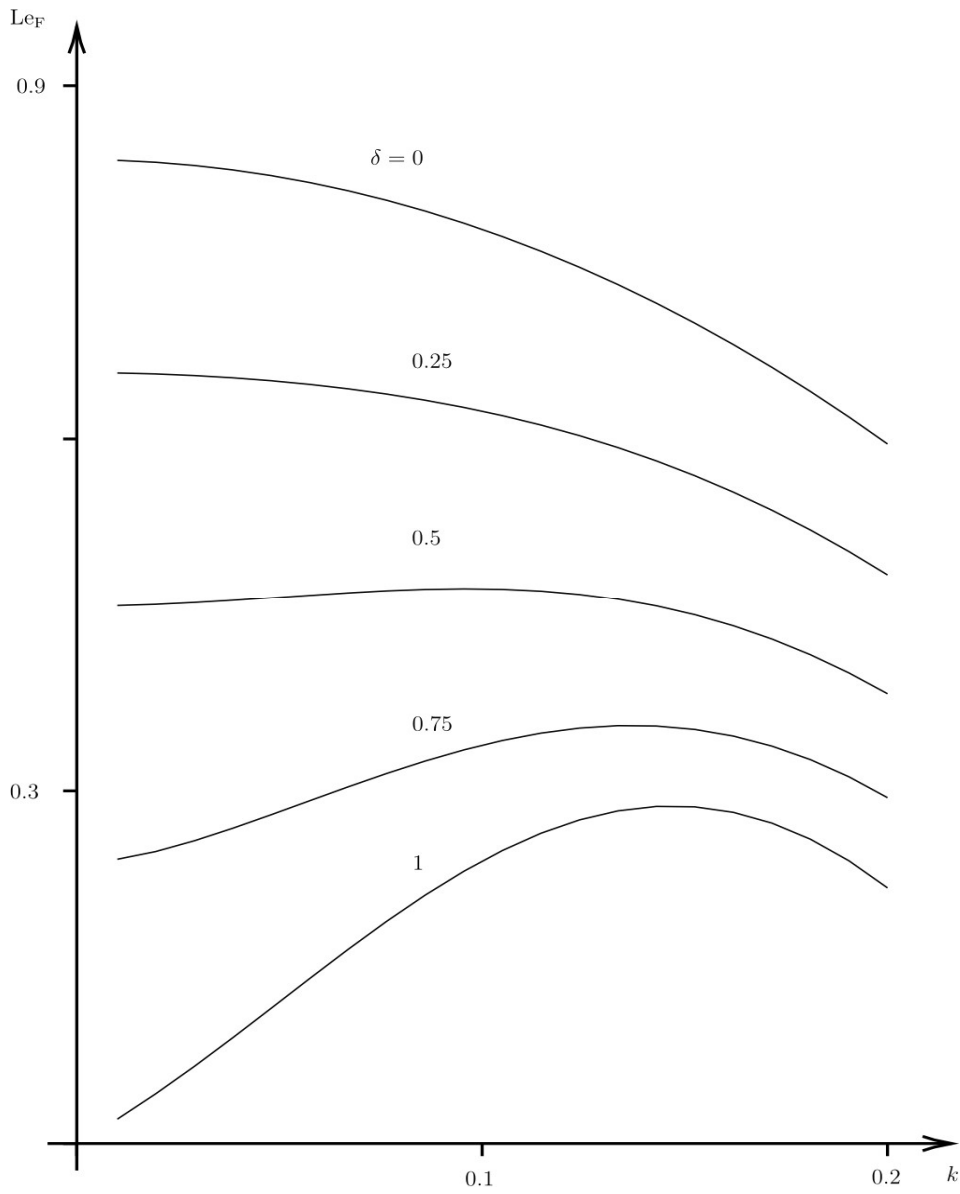
1. Briffa, E.F. & Dombrowski, N. 1970 *Proc. Roy. Soc. Lond. A* **326**, 309-322.
2. Mizutani, Y. & Nakajima, A. 1973a *Combust. Flame* **20**, 343-350.
3. Mizutani, Y. & Nakajima, A. 1973b *Combust. Flame* **20**, 351-357.
4. Polymeropoulos, C.E. 1974 *Combust. Sci. Technol.* **9**, 197-207.
5. Hayashi, S., Kumagai, S. 1974 Fifteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Penn., 445-452.
6. Polymeropoulos, C.E & Das, S. 1975 *Combust. Flame* **25**, 247-257.
7. Hayashi, S., Kumagai, S. & Sakai, T. 1976 *Combust. Sci. Technol.* **15**, 169-177.
8. Ballal, D.R. & Lefebvre, A.H. 1981 Eighteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, Penn., 321-328.
9. Atzler, F. 1999 *Fundamental Studies of Aerosol Combustion*, Ph.D. Thesis, School of Mechanical Engineering University of Leeds.
10. Lin, T.H., Law, C.K. & Chung, S.H. 1988 *Int. J. Heat Mass Transfer* **31**, 1023-1034.
11. Lin, T.H. & Sheu, Y.Y. 1991 *Combust. Flame* **84**, 333-342.
12. Silverman, I., Greenberg, J.B. & Tambour, Y. 1991 *SIAM J. Appl. Math.* **51**, 1284-1303.
13. Greenberg, J.B., A.C. McIntosh and J. Brindley, 2001, *Proc. Roy. Soc. Lond. A*, **357**, 1-31.
14. Kapila, A.K., 1981, *Int. J. Engrn. Sci.*, **19**, 495-509.
15. Zeldovitch, Ya. B., Barrenblatt, G.I., Librovich, V.B. and Makhviladze, G.M., *The Mathematical Theory of Combustion and Explosions*, Consultants Bureau, New York, 1985.
16. Joulin, G., Linan, A., Ludford, G.S.S, Peters, N. and Schmidt-Laine, C., 1985, *SIAM J. Appl. Math.* **45**, 420-434.
17. Dold, J.W., Thatcher, R.W. Omon-Arancibia, A. and Redman, J., 2002, *Proc. Comb. Inst.* , **29**, 1519-1526.
18. Dold, J.W., Daou, J. and Weber, R.W., 2004, in “*Simplicity, Rigor and Relevance in Fluid Mechanics*”, F.J, Higuera, J. Jimenez and J.M. Vega (eds) CIMNE Publishers, Barcelona.
19. Dold, J.W., Weber, R.D., Thatcher, R.W. and Sha, A.A., 2003, *Combust. Theory Modeling*, **7**, 175-203.
20. Greenberg, J.B. and Kalma, A. 1998 HTD-Vol. 361-2, *Proceedings of the ASME Heat Transfer Division, Vol. 2, Combustion and Radiation*, 3-10.
21. Buckmaster, J.D. and Ludford, G.S.S, 1982, *Theory of Laminar Flames*, Cambridge University Press, Cambridge, UK.



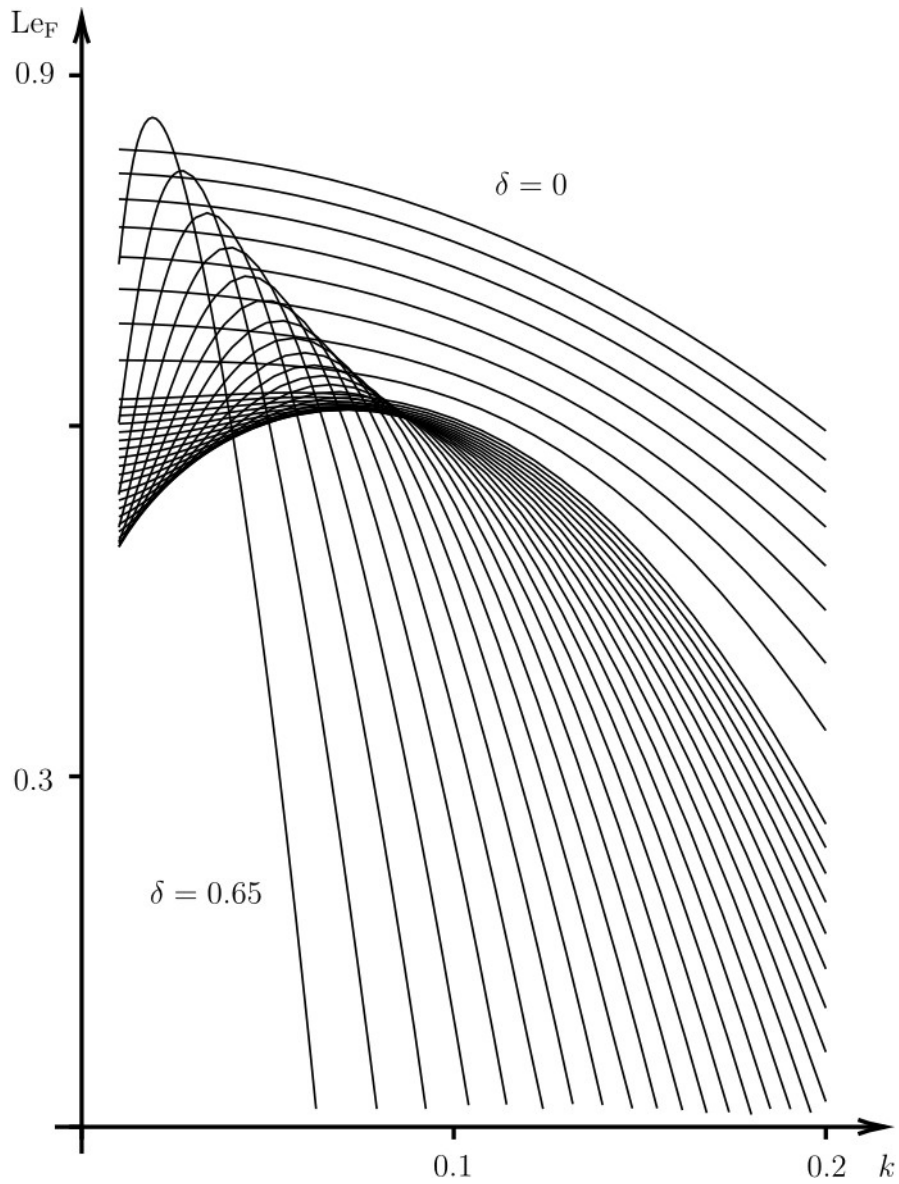
**Figure 1: Dependence of the flame speed,  $S$  (left figure) and the evaporation front location,  $d$  (right figure) on the heat loss parameter  $a$  for selected values of the initial droplet load;  $Le_z = 1, L = 0.2, T_d = 0.2, Q = 1.5$ .**



**Figure 2: Dependence of the flame speed,  $S$  (left figure) and the evaporation front location,  $d$  (right figure) on the heat loss parameter  $a$  for selected values of the heat of reaction (ii) ;  $Le_z = 1, L = 0.2, T_d = 0.2, \delta = 1$  .**



**Figure 3: Neutral stability curves for selected values of the initial droplet load;  $a = 0, Q = 1.2, Le_z = 1, L = 0.1, T_d = 0.2$ .**



**Figure 4: Neutral stability curves for selected values of the initial droplet load;  $a = 0, Q = 1.2, Le_z = 1, L = 0.3, T_d = 0.2$ .**