

# Stretch and the adiabatic burning velocity of methane- and propane-air flames

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## SHORT COMMUNICATION

# Stretch and The Adiabatic Burning Velocity of Methane- and Propane-Air Flames

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**ABSTRACT**—Results of measured adiabatic burning velocities of methane- and propane-air premixed laminar flames are presented, as obtained by the Heat Flux method. A comparison is made with results of the Counterflow method. The effect on the Counterflow method results of a non-linear instead of a linear correction for stretch is estimated. With a non-linear correction the agreement between both methods is good. It can be concluded that non-linear correction for stretch on the results of the Counterflow method is necessary in general. However, its effect may vary with varying fuel gas.

*Key Words:* Adiabatic burning velocity, laminar flames, experiments, stretch

## INTRODUCTION

An important subject of scientific combustion research is the measurement of the adiabatic burning velocity  $S_L$  of premixed laminar flames. Despite the experimental effort, still large scatter exists between the results of the various experimental methods used. This paper deals with two of these experimental methods, the Counterflow method and the Heat Flux method, which has been introduced recently (Van Maaren, Thung and De Goey, 1994).

The Counterflow method is a more or less standard method, used by many authors. An important aspect of this method is the correction for stretch, needed to obtain  $S_L$ . For varying stretch rates  $K$  the stretch-affected adiabatic burning velocity  $S_K$  is measured. In general the stretch-free adiabatic burning velocity  $S_L$  is found through linear extrapolation of  $S_K$  to zero stretch rate. For further details about this extrapolation and the Counterflow method see, e.g., Chung and Law (1988).

In Van Maaren, Thung and De Goey (1994) results of measurement of  $S_L$  of methane/air mixtures are presented, using the Heat Flux method. This method uses a special flat-flame burner, the perforated-plate burner. Most important feature of this method is that stretch-free flat flames are obtained directly. The principle of stabilization of adiabatic flat flames on the perforated plate burner is described by De Goey, Van Maaren and Quax (1993).

In this paper we will consider the results for methane- and propane-air mixtures. Comparison of the results for methane shows that the values of  $S_L$  found with the Heat Flux method are smaller than those found with the Counterflow method. Apart from small experimental errors possible in the results of the Heatflux method (e.g., radical

recombination reactions at the burner surface, see Van Maaren, Thung and De Goeij (1994)), a possible explanation is suggested by Dixon-Lewis (1992) and Tien and Matalon (1991), who performed numerical and analytical studies, respectively. According to their investigations, it can be concluded that a non-linear extrapolation to zero stretch rate is necessary. This conclusion is acknowledged by Law (1993), who states that a maximum error of about 10% may be the result of the linear extrapolation.

The differences between the results of the Heat Flux method and those of the Counterflow method are estimated using the analytical counterflow flame model of Tien and Matalon (1991). This may quantify the error in the results of the Counterflow method due to the linear extrapolation. When the error thus found is taken into account, better agreement is found between the results of the Heat Flux method and the Counterflow method.

### STRETCH CORRECTION

In the analytical model of Tien and Matalon (1991) large activation energy asymptotics is used to obtain an estimate of the adiabatic burning velocity of premixed flames (Matalon and Matkowsky, 1982). Combined with an approximate potential flow model for the counterflow configuration, the effect of the stretch rate  $K$  on the burning velocity is studied. Here, only the equations derived by Matalon and Matkowsky (1982) and Tien and Matalon (1991) are used. These papers should be consulted for further reference.

For the counterflow configuration, the relation between the stretch-affected adiabatic burning velocity  $S_K$  (as a function of the stretch rate  $K$ ) and the stretch-free adiabatic burning velocity  $S_L$  is given by

$$S_K = S_L \left[ 1 + \frac{K}{S_L} \left[ \mu_a + \frac{D_T}{S_L} \ln \left( \frac{q S_L^2}{D_T K} \right) \right] \right] \quad (1)$$

In this equation,  $D_T = \lambda/\rho c_p$  is the thermal diffusivity of the unburnt gas, while  $q$  and  $\mu_a$  are defined by

$$\begin{aligned} q &= \sigma - 1, & \sigma &= T_b/T_g, \\ \mu_a &= -\frac{D_T}{S_L} [\alpha - 1], & \alpha &= \frac{\sigma \ln(\sigma)}{\sigma - 1} + \frac{1}{2} I_0 \mathcal{L}, \\ I_0 &= \int_1^\sigma \frac{\ln(s) ds}{s-1}, & \mathcal{L} &= \frac{E[Le - 1]}{RT_g \sigma^2}. \end{aligned} \quad (2)$$

In these equations,  $T_b$  is the adiabatic flame temperature,  $T_g$  the unburnt gas temperature,  $E$  the activation energy,  $Le$  the Lewis number of the fuel gas and  $R$  the universal gas constant. Note that Equation (1) is an approximation of a more complex equation derived by Tien and Matalon (1991). For more detailed calculations of the effect of stretch on  $S_L$  the more general results in the referenced paper should be used. Here, we will use Equation (1) because it shows the influence of the various quantities on  $S_L$ , and because an estimate of the error, made when linear extrapolation is performed, can be derived easily.

Equation (1) shows that the relation between  $S_L$  and  $S_K$  is non-linear in principle. Only for small values of  $K$  linear extrapolation may be accurate enough. In experiments this will generally not be the case, because a minimum stretch rate  $K_{\min}$  is required to obtain stable counterflow flames: the unburnt gas velocity at the exit of the counterflow burners must always exceed  $S_L$ . This minimum stretch rate  $K_{\min}$  is given by

$$K_{\min} = \frac{2S_L}{H}, \quad (3)$$

in which  $H$  is the distance between both counterflow burners.

The results of Law (1993) for  $S_L$  are determined through linear extrapolation to zero stretch rate of the experimentally determined values of  $S_K$ . This can be interpreted as using the linear part  $S_K^*$  of Equation (1) in a reference point  $K = K^*$ , with  $S_K^*$  defined by

$$\begin{aligned} S_K^* &= S_L + \frac{dS_K}{dK}(K^*) \cdot K \\ &= S_L + \left[ \mu_a + \frac{D_T}{S_L} \left[ \ln \left( \frac{qS_L^2}{D_T K^*} \right) - 1 \right] \right] \cdot K. \end{aligned} \quad (4)$$

Since  $S_K \equiv S_K^*$  in  $K = K^*$ , given a value of  $K^* \geq K_{\min}$ , combination of Equations (1) and (4) yields an estimate for the error  $\Delta S_L$  in  $S_L$  when a linear extrapolation to zero stretch rate is performed instead of a non-linear extrapolation. This error  $\Delta S_L$  is the difference between  $S_L$  determined by Equation (1) and by Equation (4), yielding

$$\Delta S_L = \frac{K^* D_T}{S_L}. \quad (5)$$

This result seems rather surprising, as the adiabatic flame temperature  $T_b$ , the activation energy  $E$  and the Lewis number  $Le$  are not involved. However,  $S_K$  is defined and measured upstream of the flame, so to a first approximation the flame structure and fuel gas diffusion will not be of influence. Although Equation (5) shows no dependence on either  $E$  or  $Le$ , it should be noted that if the more general results presented in Tien and Matalon (1991) are used, careful determination of the activation energy  $E$  as function of stoichiometry may be necessary, since  $E$  is not generally a constant for varying equivalence ratio. Furthermore, the correctness of the model for  $Le \ll 1$  and  $Le \gg 1$  should be verified.

From Equation (5) it can be seen that the error increases with decreasing value of  $S_L$ . Note that only an estimate of the error can be determined, as  $\Delta S_L$  is dependent on the reference point  $K^*$  that is chosen to match Equation (1) with Equation (4).

It is assumed that the measurement of  $S_K$  has been performed in a region where  $S_K$  is an approximately linear function of  $K$ . Therefore, the value of  $K^*$  must be in a region where  $S_K$  calculated with Equation (1) is also an approximately linear function of  $K$ . To obtain an estimate for  $K^*$ , rearrangement of Equation (1) yields

$$S_K = S_L + \frac{KD_T}{S_L} \left[ \ln \left( \frac{qS_L^2}{D_T} \exp \left( \frac{\mu_a S_L}{D_T} \right) \right) - \ln(K) \right]. \quad (6)$$

The second term within the square brackets of Equation (6) must be much smaller than the first term. This leads to a maximum value  $K_{\max}$  for  $K^*$ , given by

$$K_{\max} = \frac{qS_L^2}{D_T} \exp\left(\frac{\mu_a S_L}{D_T}\right) \quad (7)$$

$K^*$  will have a reasonable value when  $K_{\min} \leq K^* \ll K_{\max}$ , which is in the region where Equation (1) is almost linear. When presenting the results in the next section the chosen value of  $K^*$  will be verified afterwards.

## RESULTS AND DISCUSSION

For  $D_T$ ,  $Le$  and  $E$  as a function of  $\phi$  the values given by Tien and Matalon (1991) are adopted. First the value of  $K^*$  in Equation (5) is to be determined. In Figure 1 two examples of calculated results with Equation (1) (continuous line) and (4) (dashed line) are shown, for a mixture of methane with air of  $\phi = 0.8$  (left Figure) and  $\phi = 0.65$  (right Figure), respectively. It is shown that for  $\phi = 0.8$  the choice of  $K^* = 450$  for matching Equations (1) and (4) is justified, as the  $S_K$  curve calculated with Equation (1) is almost a straight line. Another choice of  $K^*$  in that neighborhood will not affect the results too much. Furthermore, evaluation of  $K_{\min}$  and  $K_{\max}$  with Equations (3) and (7) yields  $K_{\min} \approx 70 \text{ s}^{-1}$  (for a typical value of  $H = 1 \text{ cm}$ ) and  $K_{\max} \approx 10^4 \text{ s}^{-1}$ , respectively.

However, for  $\phi = 0.65$  the choice of  $K$  is of large influence on the result for  $\Delta S_L$ , as can be seen from Figure 1 (right Figure). Furthermore,  $K_{\max} \approx 600$  in this case, which means that it is difficult to find an area where Equation (1) is approximately linear. This data point has therefore been left out of the analysis, as well all other data points for  $\phi \gg 1$  and  $\phi \ll 1$  giving similar results.

The experimental results of the Heat Flux method (+) and the Counterflow method of Law (1993) ( $\Delta$ ) are shown in Figures 2–3. Considering these experimental results, it appears that for propane the results of the Heat Flux method are smaller than the

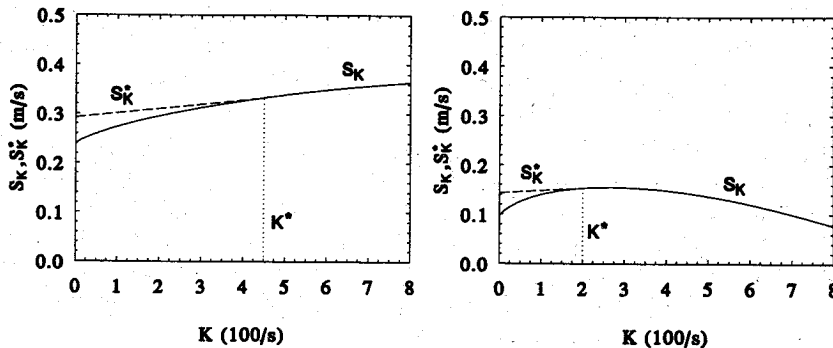


FIGURE 1 The selection of the value of  $K^*$  for calculation of  $\Delta S_L$  with Equation (5), for a methane-air mixture with  $\phi = 0.8$  (left) and  $\phi = 0.65$  (right); continuous line: according to Equation (1); dashed line: according to Equation (4).

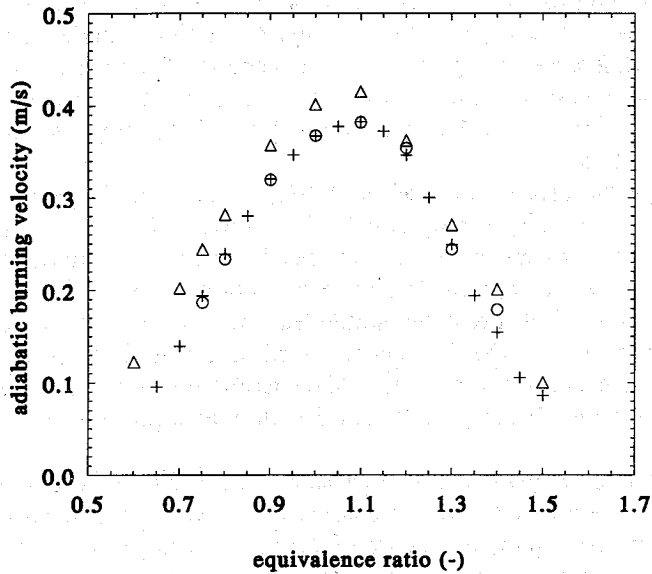


FIGURE 2 The adiabatic burning velocity of methane with air; (+) experimental results obtained with the Heat Flux method (Van Maaren, Thung and De Goey, 1994); ( $\Delta$ ) experimental results obtained by Law (1993); ( $\circ$ ) recalculated results of Law (1993), using the non-linear stretch-correction model of Tien and Matalon (1991).

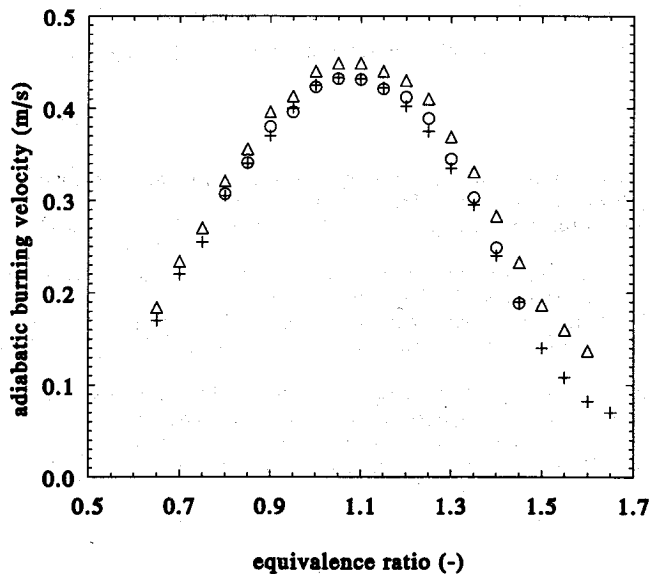


FIGURE 3 The adiabatic burning velocity of propane with air; (+) experimental results obtained with the Heat Flux method; ( $\Delta$ ) experimental results obtained by Law (1993); ( $\circ$ ) recalculated results of Law (1993), using the non-linear stretch-correction model of Tien and Matalon (1991).

results of the Counterflow method, as in the case of methane. The experimental error in the Heat Flux method results is about 1–2 cm/s. It can be concluded that, apart from the systematic difference the agreement is satisfactory. The values used for  $K^*$  are determined by matching the value of  $S_L(\phi = 1)$  as determined by the Heat Flux method with the corresponding value, corrected non-linearly for stretch, as obtained by the Counterflow method.

Next consider the corrected data of Law (1993) by using Equation (5), also shown in Figures 2–3 (○). For methane and propane  $K^* = 450$  and  $K^* = 500 \text{ s}^{-1}$ , respectively. It appears that the agreement between the results of both experimental methods is much improved when the non-linear stretch correction is applied.

The experimental results presented make clear that the linear extrapolation to zero stretch rate performed on the Counterflow method results is not accurate enough. Therefore a non-linear extrapolation should be performed, for instance with analytical equations like Equation (1), or by numerical calculations as performed by Dixon-Lewis (1992).

A significant improvement in the comparison of the results of the Heat Flux method and the Counterflow method would be possible if for a wide range of burning velocities and gas mixtures the experimental data of  $S_K(K)$ , as obtained with the Counterflow method, would become available in the literature. This would allow more accurate determination of  $K^*$ , and an estimation of the error when linear extrapolation is performed. Furthermore, the assumption of a potential flow in the analytical model of Tien and Matalon (1991) could then be verified. This may lead to a better understanding of how extrapolation to zero stretch rate should be performed.

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