Burning Velocities of Stoichiometric Methane-Hydrogen-Air Flames at Gasturbine Like Conditions

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Introduction

The present research is in the context of hydrogen addition to the natural gas supply in the Netherlands. A crucial parameter to the safety of any burner device is the laminar burning velocity. This property determines for instance the limits of flash-back and lift-off. In [4] Hermanns et al. show that the relation for the laminar burning velocity can be defined as,

$$\frac{S_L^\xi}{S_L^0} = \left(\frac{T_\mathrm{b}^\xi - T_0^\xi}{T_\mathrm{b}^0 - T_0^0} \right)^2, \tag{1}$$

with the adiabatic temperature T_b and the inner layer or cross-over temperature T_0. The superscripts 0 and ξ denote respectively to a CH_4–Air flame and a CH_4–H_2–Air flame, with ξ defined as $X_{\mathrm{H_2,u}}/X_{\mathrm{F,u}}$ and X_i being the unburnt mole fractions ($X_{\mathrm{F,u}} = X_{\mathrm{CH_4,u}}$). This result is similar to $S_L \propto (T_\mathrm{b} - T_0)^2$ which is found with the asymptotic analysis of Peters and Williams [5]. Recently de Goey et al. [2] have extended the asymptotic theory of Peters and Williams for CH_4-Air flames to CH_4-H_2-Air flames, which confirms Eq. 1.

In the present paper the extended asymptotic theory for CH_4–H_2–Air flames is used to analyse the influence of hydrogen on the propagation velocity at gasturbine like conditions. This means that gas inlet temperatures up to 600 K and pressures up to 15 bar are used. Some recent experimental data of measurements at $\xi = 0$ with higher gas inlet temperature are available in literature. In the case of increased pressure some limited experimental data for several ξ values and pressures are available as well. These experimental data will be used to verify the extended asymptotic theory at gasturbine like conditions. Due to limited experimental data with increased hydrogen content at higher gas inlet temperatures, experiments are currently carried out to extend the range of experimental data which is available for comparison.

In the next section the asymptotic theory of CH_4–H_2–Air flames will be discussed briefly. After the discussion of the extended theory some preliminary results at gasturbine like conditions will be presented. Finally, the paper ends with some conclusions and future work.

Asymptotic theory

Peters and Williams [5] started the theory from the Smooke [6] skeleton mechanism which is being reduced to a 2 step mechanism, by taking into account steady states of several radicals. It should be emphasized that the same notation is used in this paper and the classical work of Peters and Williams should be consulted for further reference. Furthermore, they assume a fixed and known relation between CO and H_2, $X_{CO} = \alpha \frac{Le_{CO}}{Le_{H_2}} X_{H_2}$. This is a valid assumption in the oxidation layer, whereas at the inner layer (and preheat zone) this is not valid anymore in the case of hydrogen addition. Here less H_2 is formed at the inner layer due to the amount of hydrogen already available at the unburnt mixture. In the theory of de Goey et al. the ratio between the production rates of CO and H_2 at the inner layer is equal to β. The relation between α and β for a given fuel mixture can be derived from the transport and boundary equations and is given by:

$$\beta = \alpha \left(\frac{1 + \xi/2}{1 - \xi\alpha/2} \right), \text{with} \quad \xi = X_{\mathrm{H_2,u}}/X_{\mathrm{F,u}}. \tag{2}$$

The global reaction in terms of ξ now becomes:

$$\mathrm{CH_4} + (2 + \xi/2)\,\mathrm{O_2} \rightarrow (2 + \xi)\,\mathrm{H_2O} + \mathrm{CO_2}. \tag{3}$$

The theory presented by de Goey et al. leads to an equation for the burning velocity (S_L) with respect to the unburnt mixture,

$$S_L^2 = \frac{8\,Y_{\mathrm{F,u}}(\xi = 0)}{15\,W_{\mathrm{F}}}\,\frac{\lambda_0}{c_{\mathrm{p}0}}\,\frac{K_{\mathrm{IV}}^{\frac{1}{2}} k_1^2}{k_{11} X_{\mathrm{H_2O},0}}\,\frac{Le_{\mathrm{O_2}}^{\frac{5}{2}} Le_{\mathrm{H_2}}^{\frac{3}{2}}}{(1+\alpha_0)^{\frac{3}{2}} Le_{\mathrm{F}} 2^{\frac{5}{2}} q^4}\,\left(\frac{T_{\mathrm{u}}}{T_0^\xi}\right)^2\,\left(\frac{T_{\mathrm{b}}^\xi - T_0^\xi}{T_{\mathrm{b}}^\xi - T_{\mathrm{u}}}\right)^4, \tag{4}$$

in which the inner layer temperature T_0^ξ is given implicitly by:

$$\frac{R T_0^\xi\; k_1^2(T_0^\xi)}{k_{11}(T_0^\xi)\; k_5(T_0^\xi)} = 1.5\,p\,\frac{Le_{\mathrm{F}}}{Le_{\mathrm{O_2}}}\,\left(\frac{1 + \xi/4}{1 + \xi/2}\right)^2. \tag{5}$$

Note that equations 4 and 5 are exactly the same as found by Peters and Williams for the $\xi = 0$ case. In oder to determine the adiabatic temperature T_{b} accurately, the following implicit expression for the change in T_{b} is used:

$$\frac{\int_{T_{\mathrm{u}}}^{T_{\mathrm{b}}^\xi} c_{\mathrm{p}}(\xi, t)\,dt}{\int_{T_{\mathrm{u}}}^{T_{\mathrm{b}}^0} c_{\mathrm{p}}(0, t)\,dt} = (1 + q_{\mathrm{H_2}}\xi)\;X_{\mathrm{F,u}}. \tag{6}$$

where $q_{\mathrm{H_2}} = 0.3116$ and $c_{\mathrm{p}}(\xi, t)$ is the temperature-dependent specific heat of the burnt gases for a given fraction ξ of hydrogen in the unburnt gases and where $T_{\mathrm{b}}^0 = T_{\mathrm{b}}(\xi = 0)$ is the adiabatic flame temperature for $\xi = 0$.

Figure 1 shows the scaled laminar burning velocities of $CH_4 - H_2 -$ Air mixtures at ambient pressures and $T_{\mathrm{u}} = 300$ K. With a significant amount of H_2 addition the results from the analysis compared with numerical simulations (Smooke mechanism [6]) and experimental data with the heat flux method by Hermanns et al. [4] agrees very well. These results of the analysis show the validility of the asymptotic theory for the influence of H_2 on the burning velocity of $CH_4 -$ Air mixtures when a significant amount of H_2 is added to the fuel.

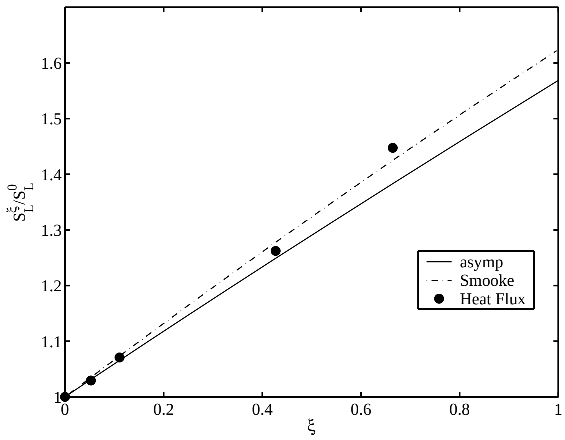

Figure 1 : The laminar burning velocity, S_L divided by S_L^0 against the hydrogen content using experiments [4] •, numerical results [6] ·— and theory —. The superscript 0 denotes the pure methane case

Towards gasturbine conditions

In this research the asymptotic theory will be validated and analysed at higher gas inlet temperatures and higher pressures with numerical modelling and new experimental data with the heat flux method [1]. For increasing T_{u} the laminar burning velocity in eq. 4 changes not only via a direct way (T_{u}) but also indirect due to T_{b}^{ξ} which is retrieved from eq. 6. Several parameters in eq. 4, e.g. $\lambda_0, c_{\mathrm{p0}}, K_{\mathrm{IV}}, k_1, k_{11}, X_{\mathrm{H_2O,0}}$ and α_0, depend on the inner layer temperature T_0^{ξ}. At increasing pressure p_{u}, T_0^{ξ} changes in eq. 5 and thereby these parameters.

In Figure 2 preliminary results of the asymptotic theory at higher gas inlet temperatures for several H_2 contents are plotted. Besides the theory some experimental data of Bosschaart et al. [1] for $CH_4 -$ Air mixtures are shown in this figure. These experimental data give an indication that the theory is able to predict these changes quite accurately.

In Figure 3 the scaled laminar burning velocity is plotted against the pressure for several hydrogen contents. The theory is compared with experimental data of Halter et al. [3]. The limited range of experimental data shows that theory predicts the experimental data very well. At higher pressures some deviation occurs.

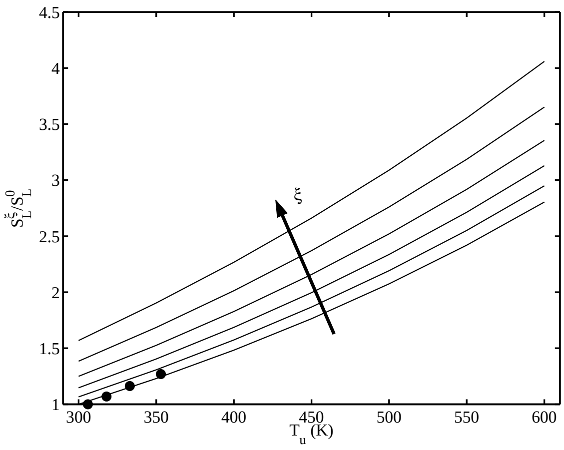

Figure 2 : The laminar burning velocity, S_L divided by S_L^0 at 300 K against the gas inlet temperature (T_u) for increasing hydrogen contents, and $p_\mathrm{u} = 1$ bar. The symbols denote measurements by [1] at $\xi = 0$ and the lines denote the theory at $\xi = 0, 0.11, 0.25, 0.43, 0.66$ and 1.

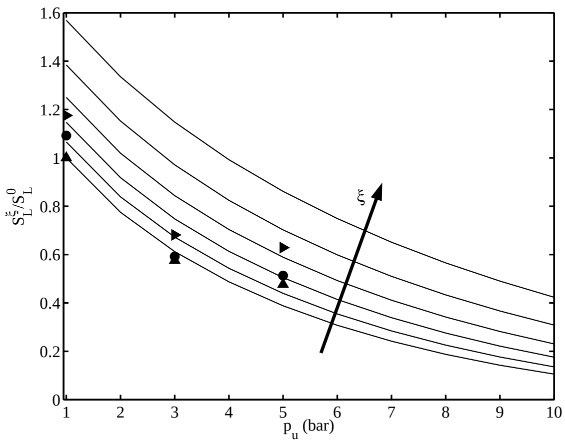

Figure 3 : The laminar burning velocity, S_L divided by S_L^0 at 1 bar against the pressure (p_u) for increasing hydrogen contents, and $T_\mathrm{u} = 300$ K. The symbols denote measurements by [3] at $\xi = 0, 0.11$ and 0.25 and the lines denote the theory at $\xi = 0, 0.11, 0.25, 0.43, 0.66$ and 1.

Conclusions and future work

The extended asymptotic theory for $CH_4 - H_2 -$ Air mixtures give promising results when comparing to experimental data which are available in literature. To verify the theory for a broather range of H_2 contents, gas inlet temperatures and pressures more experimental data are needed. Currently measurements of S_L are carried out with both increasing H_2 content and gas inlet temperature and will be presented at the conference. Numerical simulations with the skeleton mechanism of Smooke [6] will be carried out as well to validate the theory at gasturbine situations. Additionally experiments at increased pressure are planned in the near future.

Acknowledgement

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References

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