The Thermal Structure of the Flame

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Burning velocity and flame thickness are the most important parameters characterizing globally the complex processes in a combustion wave. Unfortunately there is small amount of experimental data, related to flame thickness and additionally the published date are usually based on different and incompatible arbitrary definitions. The attempt to define flame thickness on the basic of the energy equation was conducted earlier by Jarosiński [1]. The temperature in the combustion wave (Fig.1) can be expressed by the energy equation

$$\frac{d}{dz}\left(\lambda\frac{dT}{dz}\right)-c_p\rho_o u_L\frac{dT}{dz}+Q\omega=0 \qquad (1)$$

where z is the co–ordinate normal to the flame front, λ – thermal conductivity, T – absolute temperature, c_p – specific heat at constant pressure, u_L – laminar burning velocity, ρ_o – density of unburned mixture, Q – heat of chemical reaction per unit mass of fuel consumed and ω – rate of chemical reaction.

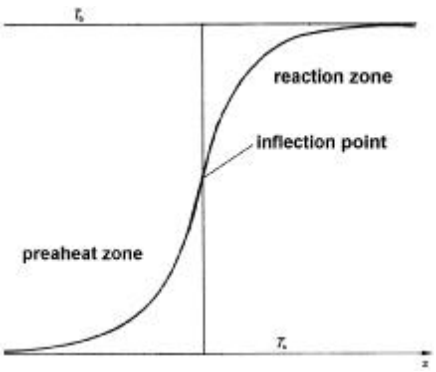

Fig.1. Temperature profile across flame front.

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It is not possible to solve Eq.(1) analytically. In [1] solution was found by means of graphical integration. Following to [1] we can introduce

$$dx = \frac{c_p \rho_o u_L}{\lambda} dz\,, \qquad \tau = \frac{T - T_0}{T_a - T_0}\,, \qquad p \equiv \frac{d\tau}{dx}$$

subscript *a* meaning adiabatic. We can obtain from (1)

$$p\frac{dp}{d\tau} - p = -\varphi F(\tau) \tag{2}$$

The boundary conditions are:

$$\tau = 0\,, \qquad p = 0 \tag{3}$$

$$\tau = \tau_m\,, \qquad p = p_m \tag{4}$$

for the preheat zone and

$$\tau = \tau_m\,, \qquad p = p_m \tag{4}$$

$$\tau = 1\,, \qquad p = 0 \tag{5}$$

for the reaction zone, where the subscript *m* is referred to the maximum value of the temperature gradient,

$$\varphi = \frac{\lambda_o \cdot Q \cdot \omega_c}{(T_a - T_o)\cdot c_p^2 \cdot \rho_o^2 \cdot u_L^2}\,, \qquad F(\tau) = \frac{\lambda \cdot \omega}{\lambda_o \cdot \omega_c} \qquad \text{and} \qquad \omega_c = \frac{1}{\lambda_o}\int_0^1 \lambda \cdot \omega \cdot d\tau$$

Equations (3) and (5) imply that $x \to -\infty$ as $\tau \to 0$ (cold boundary problem) and $x \to \infty$ as $\tau \to 1$ (hot boundary problem). By integrating Eq.(2) under the boundary conditions (3) and (5) it can be shown that the eigenvalue φ of Eq.(2) can be expressed as $\varphi = \int_0^1 p d\tau$ (Fig.2); therefore φ is equal, for $\Delta\tau = 1$, to the area under the p curve on the graph of a function $p = f(\tau)$. In other words

$$\varphi = p_M \tag{6}$$

where the subscript *M* is referred to the mean value of the temperature gradient.

The mean temperature gradient $T = f(z)$ can be expressed by the easily measured temperature curve and calculated temperature gradient $p = f(\tau)$.

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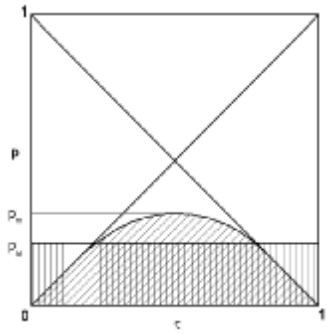

Fig.2. Temperature gradient as a function of temperature in dimensionless form with relationship between two temperature profiles, p_m and.

At the initial part of the preheat zone we have $p = \tau$. In the reaction zone the temperature gradient p decreases with τ and finally it has to meet $p = 0$ at $\tau = 1$.

The temperature profile measurements were recalculated to obtain data in $p - \tau$ coordinates. Thus having the temperature profile from experiments it is easy to determine the mean temperature gradient p_M . Making use of the temperature gradient p_M and the known temperature increase $\Delta\tau = 1$ we can determine the corresponding dimensionless flame thickness $\Delta x = \frac{1}{p_M} = \left(\frac{c_p}{\lambda}\right)\rho_u u_L \delta_M = S$,

where c_p/λ is the mean value over the temperature range of the flame and δ_M is the flame thickness resulting from the mean temperature gradient. From (6) we have

$$\varphi = \frac{1}{S} \tag{7}$$

Experimental details

The experiment was performed using a square tube equivalent to the standard 50mm×50mm flammability tube with resistance probe located at the closed top end of the tube. The mixture was ignited at the open bottom end of this tube. Temperature changes trough the flame front as a function of time were obtained using resistance probe built with 10 μm Pt 10 % Rh wire (Fig.3).

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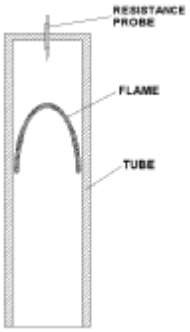

Fig.3. Diagrammatic representation of the experimental apparatus.

To find the temperature as a function the co-ordinate normal to the flame front we need to know the velocity of the upward propagating flame. Velocity was determined from the flame records made by the video camera. Computation results for the similarity number S are shown in Fig.4.

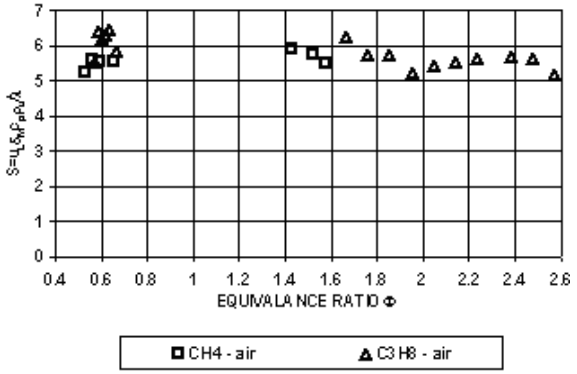

Fig.4. The similarity number S as a function of the equivalence ratio.

Conclusion

It was shown that the thickness of flames propagating in different compositions of methane – air and propane – air mixtures can be expressed by a constant similarity number $S = \left(\frac{c_p}{\lambda}\right)\rho_u u_L \delta_M = \frac{\delta_M}{\Delta} \cong 6$.

Constant value of S means that the thermal structure of all these flames is similar. Further investigations are necessary to answer the questions if the same relation is obligatory to flames propagating in other fuel – air mixtures.

References

[1] Jarosiński, J., Combust. Flame **56**, 337 (1987).

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