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SHORT COMMUNICATION

Stabilization of Adiabatic Premixed Laminar Flames on a Flat Flame Burner

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Abstract—A simple analysis and measurements are presented, which show that adiabatic premixed laminar flames can be stabilized on a flat flame burner, especially designed for this purpose. The physical properties of these flames are identical to those of flat freely propagating flames. The adiabatic state can be accomplished in practice when the burner plate temperature is well above the temperature of the unburnt mixture. The net heat loss of the flame to the burner is zero (i.e. the flame is adiabatic) when the measured radial temperature profile of the burner plate is uniform. These flames are particularly suitable for comparison with theoretical or numerical flat flame studies.

Key words: flat flames, flame stabilization, laminar, adiabatic

INTRODUCTION

One of the most important tools in laminar gas combustion research is the one-dimensional (1D) or flat flame. It is widely used in theoretical, numerical and experimental studies. In practical situations it is very difficult to produce flat flames with properties comparable to those in numerical studies. In fact, some features with respect to the flow and the heat transport processes are not entirely under control in practice. This hampers accurate comparison between experimental data and theoretical or detailed numerical studies of flat flames.

In cases when flat-flame burners are used, flat flames are stabilized mainly through heat loss from the flame to the burner surface. Consequently, the burning velocity S_L' and the flame temperature T_b' are lower than the adiabatic burning velocity S_L and the adiabatic flame temperature T_b. The operating conditions of this flame would be well defined, if the burning velocity and temperature are known accurately. However, direct measurement of the flame temperature is presently still a very delicate task, which can be performed only with moderate accuracy: an absolute error of about 50 to 100 K is usually inevitable.

On the other hand, the adiabatic flame temperature of a given mixture can be calculated quite accurately. To produce adiabatic flames experimentally, usually the opposed jet or similar burners are employed, using flow divergence to stabilize these flames, as described in Law (1993). Since the flow in these flames is clearly more—dimensional, several assumptions concerning e.g. the flow pattern are introduced, before comparison with 1D numerical results is possible. However, if an adiabatic flat flame with a 1D flow field could be stabilized on a flat-flame burner, then comparison of the flame structure with model predictions would become much more accurate.

In this paper it is shown, that flat adiabatic methane/air flames can be stabilized on a flat-flame burner, especially designed for this purpose. The flame is stabilized by heat loss to the "hot" burner. However, the burner plate on its turn transfers heat to the cold unburnt mixture. The flame is adiabatic, when the net heat loss to the burner plate is zero. Errors in flame temperature and burning velocity are of the order of 10 K and 0.5 cm/s, respectively.

In the next two sections, we shall review some important features of freely propagating adiabatic flames, and we will show that the flame properties of these flames are equal to those of burner-stabilized adiabatic flames. Some experimental results will be presented in the last section.

FREELY PROPAGATING ADIABATIC FLAMES

The energy equation of an ideal 1D flame may be written as:

$$\dot{m}c_p\frac{\partial T}{\partial x} - \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) = S_T, \tag{1}$$

where $\dot{m} = \rho u$ is the constant mass flux, c_p the constant-pressure specific heat, λ the thermal conductivity of the gas and S_T the heat source by chemical reactions.

In figure 1, a schematic view of part of the temperature profile $T(x)$ of a freely propagating adiabatic flame is given (continuous line). Regarding this, a point x_c may be introduced, defining a region $-\infty < x < x_c$ in which S_T may be assumed to be zero. This region is sometimes referred to as the preheating zone of the flame. Integrating (1) from $x = -\infty$ to a point $x < x_c$, taking into account that $\partial T/\partial x = 0$ for $x = -\infty$, gives:

$$\lambda\frac{\partial T}{\partial x}(x) = \dot{m}c_p[T(x) - T_0], \tag{2}$$

with $T_0 = T(-\infty)$. This equation yields the following general expression for $s_L = u$:

$$s_L = \frac{\lambda}{\rho c_p(T_c - T_0)}\frac{\partial T}{\partial x}\Big|_{x=x_c}, \tag{3}$$

where $T_c = T(x_c)$. The derivative $\partial T/\partial X$ at $x = x_c$ is uniquely defined by the energy equation (1) in the reaction zone $x > x_c$, combined with the boundary conditions $T = T_c$ at $x = x_c$ and $T = T_b$ at $x = +\infty$, and may be determined exactly when S_T is known. As many authors have shown (see Williams (1985) for an overview), explicit expressions for S_L can be derived from (3), when the chemical scheme is reduced, and further assumptions are introduced.

BURNER STABILIZED ADIABATIC FLAMES

A rotationally symmetric flat flame burner, with radius $R = 14$ mm, is now placed in the gas flow. The burner plate is perforated with holes of radius $r_p = 0.2$ mm in a regular pattern, and has a porosity $\sigma = 0.4$. In the (axial) direction of the flow the burner plate extends from $x = 0$ to $x = x_p = 1.8$ mm, as indicated in figure 1. At $r = R$, the burner plate is maintained at a constant temperature T_R by means of an external cooling jacket. T_R is chosen such, that $T_0 \leq T_R \ll T_c$. Any heat flux to the burner plate will be conducted to the cooling jacket by some radial temperature gradient in the burner plate. It can be shown easily, that the radial temperature profile $T_p(r)$ of the burner plate is described by a second-order polynomial of the radial distance r, assuming that the heat flux from the flame to the burner plate is uniformly distributed, and that the axial temperature variation in the burner plate is much smaller than the radial variation.

In conventional flat-flame burners, one usually chooses T_R to be (almost) equal to T_0. Heat transfer to the burner by conduction is the main stabilizing mechanism of flames

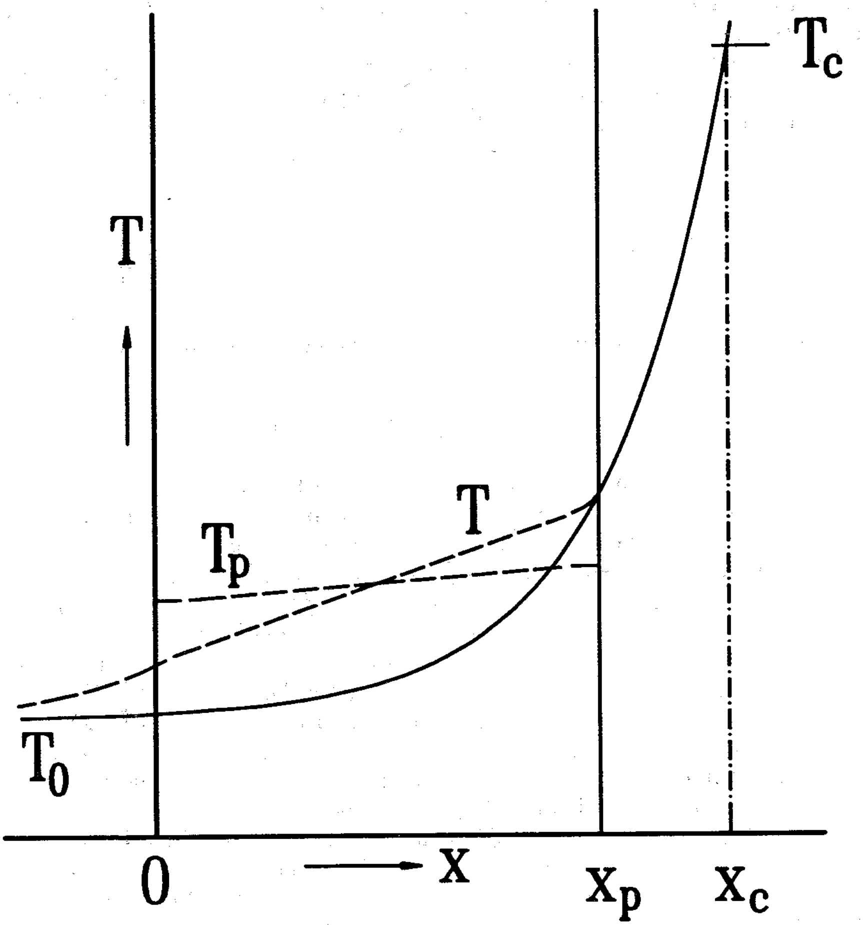

FIGURE 1 Axial temperature profiles; continuous line: freely propagating adiabatic flame; dashed lines: burner stabilized adiabatic flame (T) and burner plate (T_P)

on these burners, implying that $\partial T/\partial x > 0$ at $x = x_p$. Therefore, these flames are adiabatic only when they blow off (or $\partial T/\partial x = 0$ at $x = x_p$). In practice however, under influence of the surrounding atmosphere and geometrical irregularities in the burner plate, blow-off is induced long before the adiabatic limit is reached.

The situation is different, when T_R is significantly higher than T_0. The unburnt gas is now heated by the burner plate. As a result, the local adiabatic burning velocity at exit of the burner plate is increased above the local gas speed. Therefore, the flame will not (partially) blow off, but remain flat, and will stabilize on the burner through heat loss to the burner plate. In the adiabatic case, when $u = s_L$, the heat loss of the flame equals the heat gain of the unburnt gas. Consequently, the radial temperature gradient in the burner plate vanishes. Since the heat flows to and from the burner plate are now equal and non-zero, the flame is stable because $\partial T/\partial x > 0$ at $x = x_p$, and adiabatic because energy is preserved over the burner plate. The flame appears to be stable in practice, when $T_R - T_0$ is about 50 K. Note that for stabilization of the flame, the actual value of T_R has no significance once the adiabatic state is established, as long as T_R is high enough to prevent partial blow-off. Only the stand-off distance of the flame alters with varying values of T_R.

Now the question arises, how the physical properties of this flame (temperature and mass-fraction profiles, burning velocity, etc.) compare with those of a freely propagating flat flame. The energy equations of the adiabatic burner-flame system are considered to investigate this problem. The energy equation of the gas can be written as:

$$\sigma\rho\left(\frac{u}{\sigma}\right)c_p\frac{\partial T}{\partial x}-\frac{\partial}{\partial x}\left(\lambda\sigma\frac{\partial T}{\partial x}\right)=S_T+\frac{2\alpha\sigma}{r_p}(T_p-T) \tag{4}$$

Conservation of energy within the burner plate material, with thermal conductivity λ_p, leads to the following equation for the axial temperature profile $T_p(x)$ of the burner plate:

$$-\frac{\partial}{\partial x}\left(\lambda_p(1-\sigma)\frac{\partial T_p}{\partial x}\right)=-\frac{2\alpha\sigma}{r_p}(T_p-T) \tag{5}$$

In these relations, α is the heat transfer coefficient between the gas and the plate within the perforations. For $x > x_p$ and $x < 0, \alpha = 0$ and $\sigma = 1$. The ambiguity in velocity at $x = 0$ and $x = x_p$ may be disregarded. Note that all conductive heat transport terms in radial direction are omitted in (4) and (5) for the adiabatic situation.

Since the burner plate has no radial temperature profile, integration of the left-hand side of (5) from $x = 0$ to $x = x_p$ must yield zero. Consequently, when (4) and (5) are added and integrated from $x = -\infty$ to a point $x_p < x < x_c$, we arrive at the same results (2) and (3) as for the freely propagating flame. Further, the boundary conditions $T(x_c) = T_c$ and $T(x = +\infty) = T_b$ are also unchanged, meaning that the temperature profile $T(x)$ for $x > x_p$ and the burning velocity are equivalent to the corresponding properties of a free adiabatic flame. Analogously, it can be shown that the species mass fraction profiles are also unchanged. Small differences between the two flames may occur in practice in the area near $x = x_p$, due to surface reactions and small flow disturbances, induced by the presence of the burner. Further, the assumed heat transfer model between the gas and the burner plate (last term on the right-hand side of both (4) and (5)) does not imply a special case. The conclusions mentioned above can be drawn using any other heat transfer model as well.

The profiles of temperature (and mass fractions) of the two flames are different for $x < x_p$, as is clearly seen in figure 1, also presenting a plot of the solution of the coupled energy equations (4) and (5) (dashed lines). Note that the total area between the curves of T and T_p is zero, indicating that the heat flows from the flame to the burner and from the burner to the gas cancel out. We may conclude that the burner plate induces some kind of heat recirculation to the upstream part of the burner, similar to what is described by Sato and Takeno (1979). However, in contrast to the present study, their flames are burning within the burner plate, so that $S_T \neq 0$ for $0 < x < x_p$, and $x_c < x_p$.

EXPERIMENTAL RESULTS

In the preceding analysis we have shown that the burner-stabilized flame is adiabatic when all radial heat flows in the burner are zero, i.e. when the temperature profile of the burner plate is flat. To investigate this, we measured the radial temperature profile of the burner plate with small thermocouples attached to the upstream side of the burner plate. An example of the measured radial temperature profiles of the burner plate is shown in figure 2, for varying values of the gas speed. The use of the thin brass burner plate assures that the measurements are sensitive to small changes in the heat flow through

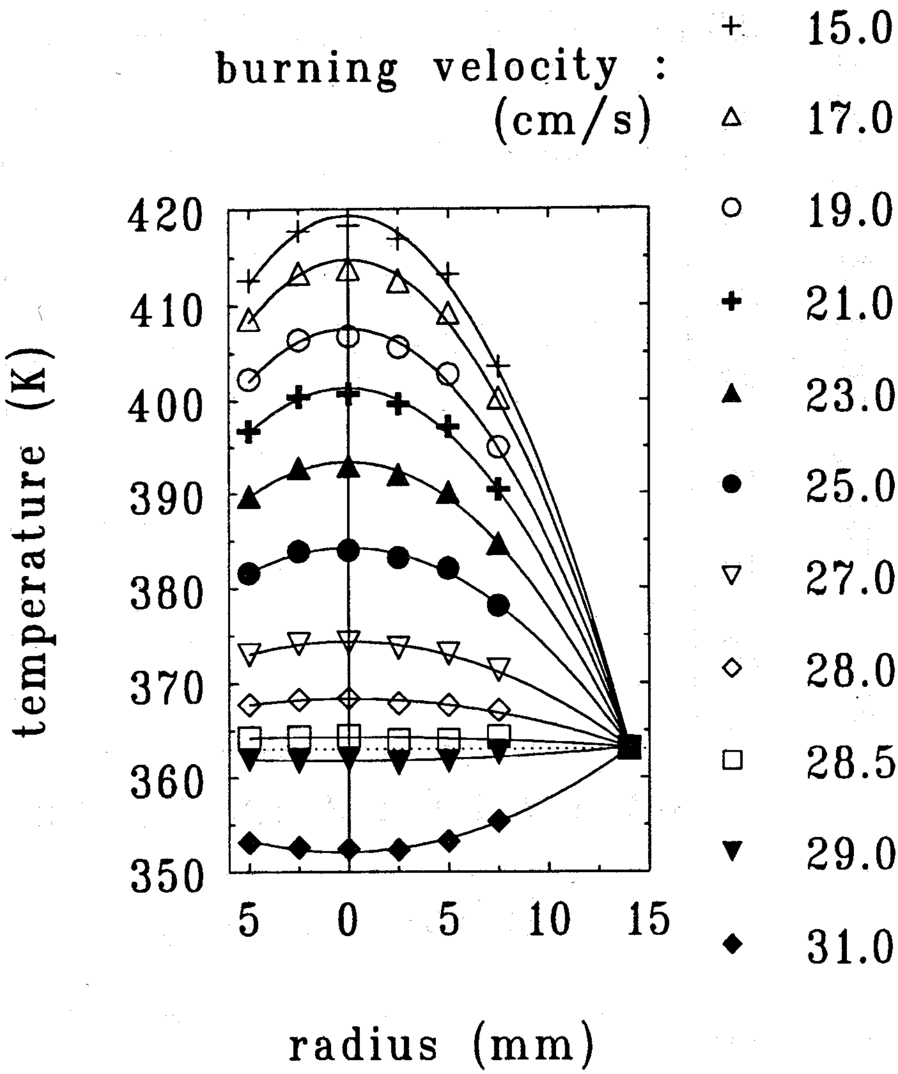

FIGURE 2 Radial temperature profiles burner plate; markers: measurements; lines: second-order polynomial fit

the plate, i.e. small variations in the flow velocity. Further, although there is an axial temperature variation in the burner plate, the measured plate temperature is a valid quantity for $T_p(r)$, since $\lambda_p \gg \lambda$. The methane/air mixture used in the experiments has an equivalence ratio of $\phi = 0.8$ and an initial temperature of $T_0 = 293$ K. The temperature of the cooling water was set to $T_R = 363$ K. This proves to be sufficient to create adiabatic flames. Clearly seen is that the burner plate temperature is uniform at the adiabatic burning velocity $S_L = 28.7$ cm/s. This value for S_L is in close agreement with recent data on burning velocities, compiled by Law (1993). At lower gas speeds there is a net heat flux from the gas to the burner plate, yielding a reduced flame temperature. At higher gas speeds there is a net heat flux from the plate to the gas. This yields a

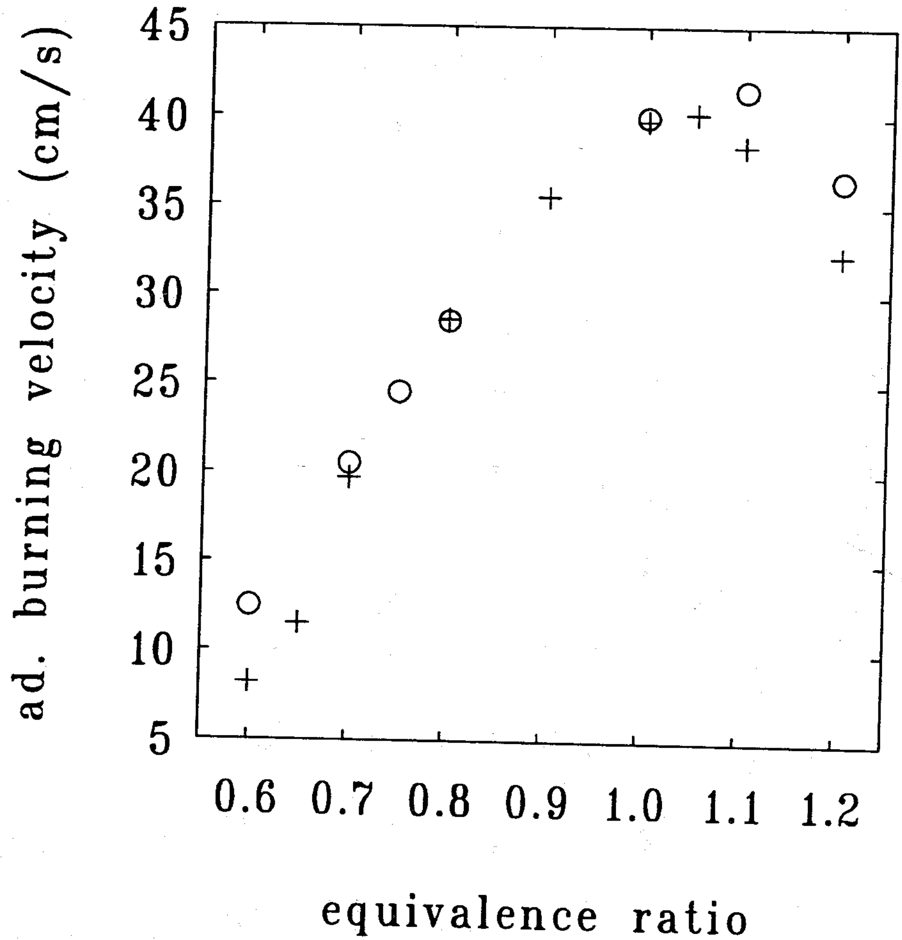

FIGURE 3 Adiabatic burning velocity as function of equivalence ratio; cross markers: this work, circle markers: data compiled by Law (1993)

flame temperature which is higher than the adiabatic flame temperature. Note that the measured temperature profiles show that this flame is not blown off partially, since the measured profiles are all well described by second-order polynomials. This is confirmed by visual observation of the flame. The burning velocity can be adjusted to its adiabatic value within a range of 0.5 cm/s. Furthermore, measurement errors in $|T_p(0) - T_p(R)|$ of 0.5 K indicate that the error in T_b is about 10 K.

We performed the same measurements as presented in figure 2 for equivalence ratios ranging from $\phi = 0.6$ to 1.2. The results of the adiabatic burning velocities are presented in figure 3, together with the data obtained by Law (1993). As can be seen from the figure, excellent agreement is obtained for lean mixtures with moderate burning velocities. At burning velocities near the lower flammability limit the error increases, because the burner plate temperature differences are very small at these low burning rates, so that it is more difficult to determine when these temperature differences are zero. For rich mixtures the results are still to be improved. The error is probably caused by more-dimensional effects like the secondary diffusion flame above the partially burnt premixed flame, or heat loss to the environment before combustion is completed.

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