Pressure wave interactions with rippled premixed flames - effect of Lewis number

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Introduction

It has been demonstrated (Teerling, McIntosh, Brindley and Tam 2003) that oscillatory pressure disturbances can cause a rippled flame to have a strongly increased mass burning rate as illustrated in Fig. 1. By numerically modelling the premixed flame using single one step Arrhenius kinetics and using the flux corrected transport algorithm LCPFCT developed by Oran and coworkers at the US Naval research Laboratory at Washington (Oran and Boris 2001), it has been possible to track the flame as it undergoes the Rayleigh-Taylor instability for the initial part of the cycle of a harmonic pressure wave imposed on the flame, followed by the flame returning close to its original shape when the pressure gradient is in the opposite direction. However it does not come back to exactly the same shape, since vorticity has been created due to the baroclinic terms. As the cycle of pressure wave fluctuations is followed, the flame becomes more and more distorted. The results of this work with Lewis number at unity are summarised in Fig. 2 which shows the normalised time-averaged mass burning flux plotted against frequency for three wavenumbers.

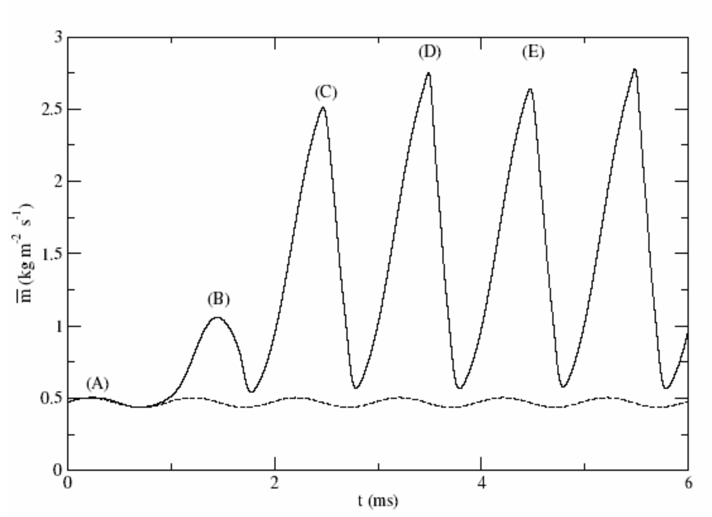

Fig. 1 Net mass burning flux, normalized per unit surface of unperturbed flame, as a function of time for two-dimensional (solid line) and for one-dimensional flame (dashed line) Δp = 0.05 bar; f = 1000 Hz);

The effect of Lewis number

In this paper we now consider the effect of Lewis number on these results, knowing that we will be likely to encounter the effect of the thermal-diffusion instability at low Lewis numbers.

Initially we considered a flame that had the same properties as before, but with the Lewis number set to 2.0. This represents a lean, heavy-fuel flame or a rich, light-fuel flame. For this Lewis number, an initial burning velocity, S_{u0} of 0.46 m/s was obtained. The evolution of the non-dimensional mass burning flux $\overline{m}/\overline{m}_0$ was again evaluated against time, together with two

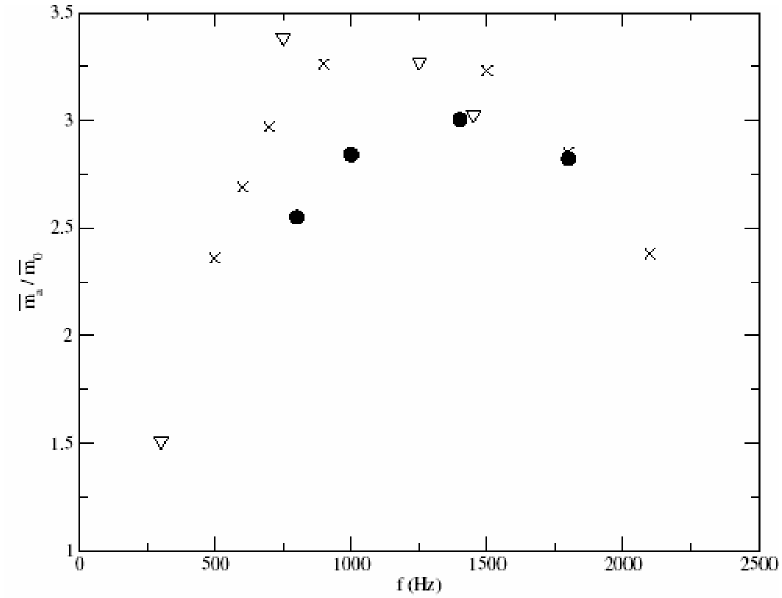

Fig. 2 Normalized time-averaged mass burning flux $\overline{m}_a / \overline{m}_0$ versus frequency for three wavenumbers: k = 0.056 (open triangles); 0.077 (black circles) and 0.101 (crosses); Δp = 0.05 bar.

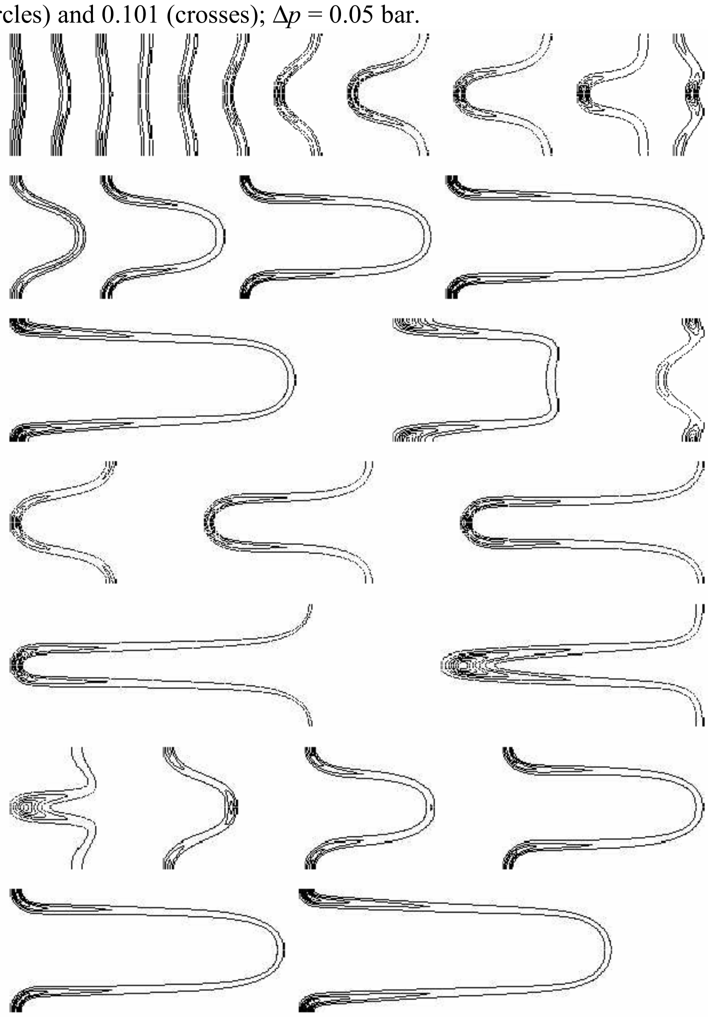

Fig. 3 Contour plots of reaction rate for same case (f = 1000 Hz; Δp = 0.05 bar; k = 0.079; Le = 2.0) for t = 0.16, 0.32, 0.47, 0.63, 0.79, 0.95, 1.11, 1.27, 1.42, 1.58, 1.74, 1.90, 2.05, 2.20, 2.35, 2.50, 2.65, 2.81, 2.96, 3.11, 3.26, 3.42, 3.58, 3.72, 3.88, 4.03, 4.19, 4.35, 4.50 ms after the pressure was imposed.

similar flames of a different Lewis number (Le = 1.0 and 0.5). The frequency and amplitude of the imposed pressure wave were set to f = 1 kHz and Δp = 0.05 bar. The results showed that the evolution of the three different flames was quite similar, albeit near the maxima in the dynamic equilibrium phase, the gradients near the maxima in mass burning flux $\overline{m}$ became sharper for increasing Lewis number. However the total mass burnt M was quite similar as were the values of the average new mass burning $\overline{m}_a$ and the delay time t_d .

Holes in flame front

Despite the fact that the mass burning flux did not differ much when the Lewis number was dropped, the wrinkled flame front developed a very different shape from that seen for the case Le = 1.0. To illustrate this, a sequence of reaction rate contours is plotted in Fig. 3. These contours showed that the reaction along the wrinkling was initially quite uniform, but at later stages the reaction took place mainly in those parts of the wrinkled flame that were pointing towards the burnt gases. The difference in thickness of the reaction zone along the flame front grew with every cycle and eventually the flame extinguished locally in areas where the flame finger shape pointed towards the unburnt region.

This phenomenon can be explained by the fact that for a low value of the Lewis number, the heat diffusivity is greater than the mass diffusivity. Because of this imbalance, there is not enough mass supplied to the flame front to sustain the initial reaction rate. As a consequence of this the temperature dropped. Due to the wrinkled shape of the flame front, areas where the burnt mixture was penetrating the unburnt gases, were most affected.

As a result of local quenching, the amount of released heat dropped, and consequently less mass was added to the unburnt gases. This drop in the temperature locally yields a different shape of the temperature profile, and thus clearly shows differences in flame thicknesses along the flame.

Lewis number *Le* = 0.5

We now consider the case Lewis number Le = 0.5, which could either represent the case of a premixed flame using a lean, light-weight fuel such as hydrogen, or a rich, relatively heavy fuel such as butane. Keeping all the other parameters the same as in the aforementioned "default" case, this parameter setting yielded a burning velocity S_{u0} = 0.34 ms^{-1}. The evolution of the mass burning flux versus time for this case is plotted in Fig. 4, together with time sequences for the case of a flame with Le = 1.0 and 2.0; imposed on these flames was the "default" pressure wave (i.e. f = 1kHz; Δp = 0.05 bar). A similar plot is given in Fig. 5, but in this plot each of the sequences in mass burning flux $\overline{m}$ is scaled with its associated initial value of the mass burning

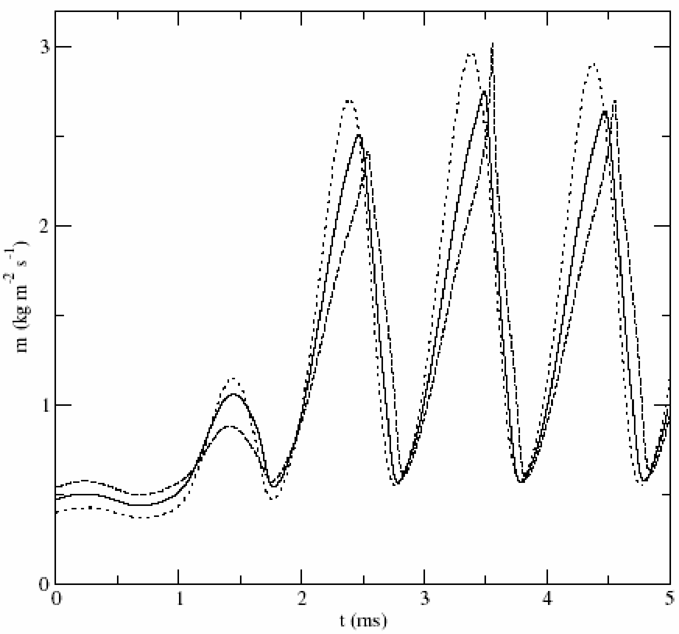

Fig. 4 Evolution of the mass burning flux $\overline{m}$ for three flames with different Lewis number: Le = 1.0 (solid line), Le = 0.5 (dotted line) and Le = 2.0 (dashed line).

flux $\overline{m}_0$, yielding plots of the non-dimensional mass burning flux. Because the value of $\overline{m}_0$ was different for these three flames, the plot shows that the relative increase in mass burning flux becomes greater as the Lewis number decreases.

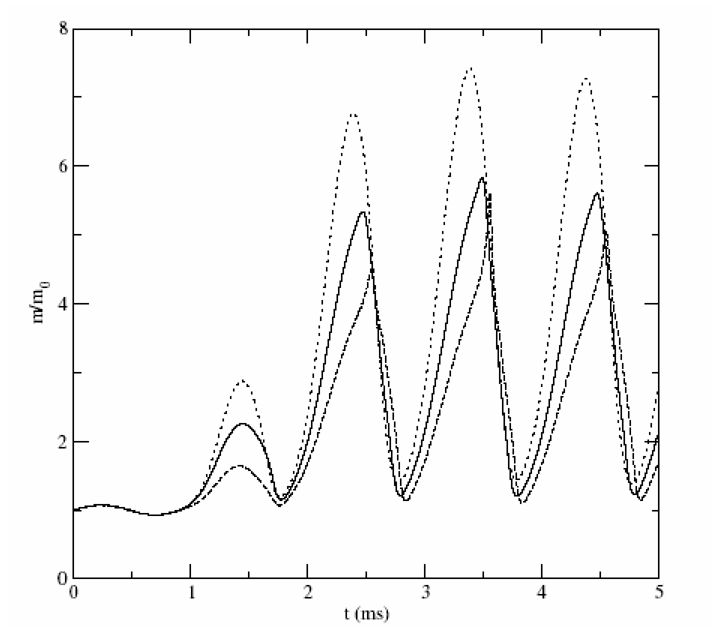

Fig. 5 Evolution of the nondimensionalised mass burning flux ($\overline{m}/\overline{m}_0$) for three flames with different Lewis number: Le = 1.0 (solid line), Le = 0.5 (dotted line) and Le = 2.0 (dashed line)

This behaviour is also reflected in the values obtained for the ratio that indicates the time-averaged increase in mass burning flux, $\overline{m}_a/\overline{m}_0$. These values are shown in Table 1. The table also shows the values obtained for the delay time t_d and the amplitude of the mass burning flux $\Delta\overline{m}$.

Conclusions

There is no doubt that the effect of Lewis number is marked when a rippled flame encounters an oscillating pressure disturbance. In particular this work shows that there is an important enhancement of mass burning rate growth for Lewis numbers less than unity.

f (Hz)	Δp (bar)	k	t_d (ms)	$\bar{m}_a$ (kg/s m^2)	$\Delta\bar{m}$ (kg/s m^2)	$\bar{m}_a/\bar{m}_0$	Le
1000	0.05	0.079	1.64	1.68	1.19	4.18	0.5
1000	0.05	0.079	1.60	1.55	1.06	3.27	1.0
1000	0.05	0.079	1.75	1.54	1.12	2.83	2.0

Table 1 Time-averaged increase in mass burning flux, $\overline{m}_a/\overline{m}_0$, the delay time t_d and the amplitude of the mass burning flux $\Delta\overline{m}$.

References

Teerling, O.J., McIntosh, A.C., Brindley, J. and Tam, V.R.Y. *Premixed flame response to Oscillatory Pressure waves* Proc. Inst Comb. Vol. 30, 2003.

Oran, E.S. and Boris, J.P. *Numerical Simulation of Reacting Flows*, 2nd Edition, Cambridge University Press, Cambridge, U.K., 2001.