Scale Effect on the Flame Initiation in Lean Near-Limit Hydrogen–Air Mixtures

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Introduction

Experimental observations of weak lean H_2–air flames in closed combustion chamber [1] showed that, during upward flame propagation, the hydrogen concentration decreases near the chamber wall. This phenomenon, associated with the high diffusivity of hydrogen, can affect flammability limits, especially in small-scale experiments under microgravity. In the present study, we numerically analyzed the scale effect on the extinction conditions for a very lean H_2–air mixture (ϕ = 0.0851), which is close to the limit predicted numerically by Ronney and co-workers [2]. For outwardly propagating spherical laminar premixed flames, we employed a one-dimensional model based on a detailed kinetic mechanism and real transport and radiative properties of optically thin gases. Effects of radiation reabsorption, gravity, pressure gradient, and thermal diffusion were assumed to be negligible. Numerical results for flame evolution were obtained by integrating the well-known time-dependent equations for mass, energy and species concentrations. The reaction scheme involved 8 species and 26 reactions. The combustion process was numerically initiated by hot combustion products acting as an ignition source. More details on the governing conservation equations, boundary conditions and radiation model can be found in [3].

Results and discussion

We analyzed numerical results for two computational domains with radii R_0 = 6 and 12 cm. The computations were performed for an ambient temperature of 373 K and pressure of 0.1 MPa. Results obtained with and without radiation are presented.

In Fig. 1a, dotted and solid curves represent flame front histories with and without radiation, respectively. For the domain with R_0 = 6 cm, the flame behavior without radiation effects (curve *2*) is different from that observed in the optically thin limit (curve *4*), i. e. radiative loss strongly influences the near-limit flame behavior of lean hydrogen–air mixtures. Curve *2* illustrates the evolution of an extinguishing flame. In this case, flame extinction is caused by hydrogen depletion in the vessel, due to hydrogen diffusion from the periphery toward the flame kernel. This follows from calculations of the hydrogen concentration in the wall layer (Fig. 1b). In the zero-radiation approximation (curve *2*), the flame is quenched when the H_2 concentration decreases by 20% of its initial concentration. The optically thin flame (curve *4*) is extinguished when the near-wall hydrogen concentration decreases by a much smaller relative amount.

In Fig. 1a, curves *1* and *3* represent the results computed in the domain with R_0 = 12 cm. Comparing curves *1* and *2*, we see that an increase in the domain radius can result in a change from extinction to flame propagation as computed in the zero-radiation approximation. Figure 1b shows that this effect is due to the slower hydrogen depletion in a larger combustion domain.

Our numerical simulations revealed that a quasi-steady flame kernel exists in the optically thin limit. Curve *3* in Fig. 1a represents a kernel evolving into a stationary flame ball. The flame radius remains equal to 3.3 mm during an interval of 39 s. The limited lifetime is explained by hydrogen depletion in a finite computational domain. The flame-ball temperature remains virtually constant during a long time, varying within 1160–1175 K. The adiabatic flame temperature, T_{ad}, is about 655 K for the initial mixture, whereas the calculated flame-ball temperature is close to the adiabatic value for the 10% H_2–air mixture (T_{ad} = 1162 K). This implies that lean near-limit combustion of hydrogen–air mixtures is strongly affected by hydrogen diffusion. The H_2O concentration in combustion products calculated for H_2–air mixture with ϕ = 0.0851 ranged from 11 to 14 vol. %, whereas the equilibrium value is 3.5 vol. %. Thus, the important role played by radiative loss in determining the temperature history inside a flame ball is explained by the high concentration of the emitting H_2O in the combustion products.

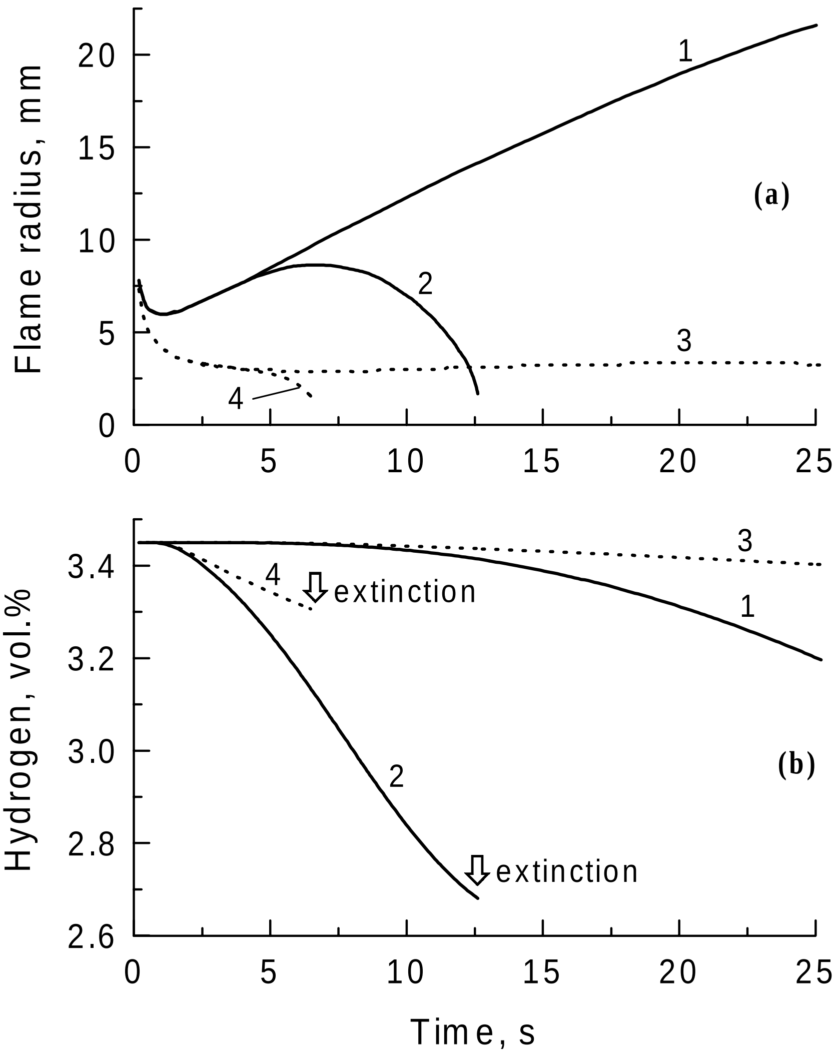

Fig. 1. (a) Flame front radius and (b) hydrogen concentration in the wall layer for the near-limit 3.45% H_2–air mixture (ϕ = 0.0851). Dotted and solid curves represent flames with radiation (optically thin limit) and without radiation, respectively. Computational domain: R_0 = 6 cm (curves *2* and *4*) and R_0 = 12 cm (curves *1* and *3*).

Conclusions

The model can be used to analyze the influence of the length scale of an experimental facility on the characteristics of developing flame kernels. In a relatively small vessel, a hydrogen-lean near-limit flame can die out even after it has propagated beyond the minimal critical radius. In the case without radiation, this phenomenon is explained by a decrease in hydrogen concentration in the unburned mixture.

References

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