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Effect of radiation losses on very lean methane/air flames propagating upward in a vertical tube

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ABSTRACT

The stationary upward propagation of a very lean methane/air flame in a long vertical tube open at the bottom and closed at the top is simulated numerically using a single overall chemical reaction to model combustion and assuming an optically thin gas and a transparent or non-reflecting tube wall to approximately account for radiation losses from CO_2 and H_2O. Buoyancy plays a dominant role in the propagation of these flames and causes a large region of low velocity of the burnt gas relative to the flame to appear below the flame front when the equivalence ratio is decreased. The size of this region scales with the radius of the tube, and its presence enhances the effect of radiation losses, which would be otherwise negligible for a standard flammability tube, given the small concentration of radiating species. Heat conduction is found to be important in the low velocity region and to lead to a conduction flux from the flame to the burnt gas that causes extinction at the flame tip for a value of the equivalence ratio near the flammability limit experimentally measured in the standard tube. The effect of radiation losses decreases with the radius of the tube. Numerical results and order-of-magnitude estimates show that, in the absence of radiation, a very lean flame front fails to propagate only after recirculation of the burnt gas extends to its reaction region and drastically changes its structure. This condition is not realized for the standard flammability tube, but it seems to account for the flammability limit measured in a tube of about half the radius of the standard tube.

1. Introduction

Upward propagation of flame fronts in tubes filled with very lean reactive mixtures is a problem of both fundamental and applied interest which has been extensively studied. On the basis of a comprehensive analysis of previous work, Coward and Jones [1] proposed that a standard flammability tube can be used to characterize the flammability of gas mixtures. This is a vertical tube 51 mm in diameter and 1.8 m long with an open lower end and a closed upper end, which is filled with the mixture to be tested. This mixture is ignited near the lower end of the tube, and it is said to be flammable if a flame ensues and propagates all the way to the upper end. Levy [2] noted that buoyancy plays a dominant role in the propagation of the flame front near the flammability limit. This author observed that, when the Lewis number of the fuel is not far from unity, as in mixtures of methane/air or propane/air, the flame front consists of a spherical cap followed by a long skirt, and that its velocity is close to the velocity of a bubble rising in the tube [3]. The dependence of the flammability limit on the diameter of the tube was studied by Babkin et al. [4]. In agreement with some previous results but contrary to the results of Coward and Jones, these authors found that the minimum fuel concentration for which a flame front can propagate increases with the diameter of the tube. Lewis and von Elbe [5], Jarosinski et al. [6] and Hertzberg [7] pointed out that the stretch of the flame due to its curvature and to the strain rate of the flow it induces in the tube may cause the extinction observed at the flammability limit. Von Lavante and Strehlow [8] approximately computed the flow of the fresh gas above the flame front. They found that the stretch is due mainly to the strain rate of the flow; that it is of the order of the inverse of the residence time of the gas across a planar flame propagating in the mixture; and that it is maximum at the tip of the flame front, where extinction begins at the flammability limit. The flow on both sides of an axisymmetric steadily rising flame front was further investigated by Higuera [9], with emphasis on the structure of the vortical flow downstream of the flame front and the generation of vorticity at the flame. The results accurately determine the shape and stretch of the flame and point out a

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possible instability of the vortical flow. Shoshin et al. [10] recently investigated the effect of preferential diffusion, which can increase the final combustion temperature of stretched flames when the Lewis number of the deficient reactant is smaller than unity. These authors, however, conclude that preferential diffusion cannot always explain the observed behavior of methane/air and propane/air flame fronts at their flammability limits. Shoshin and Jarosinski [11] and Shoshin et al. [12] proposed that heat losses from the flame due to the effect of radiation in a low velocity region that appears below very lean flames may explain the observed extinction.

Radiation losses in near limit flames propagating upward in a tube are further investigated in this paper. Numerical computations and order-of-magnitude estimations are used to show that the effect of these losses is very much enhanced by the conditions of the flow below the flame front. For very lean mixtures, this flow features a region of low velocity relative to the flame, whose radial extent scales with the diameter of the tube and whose length may be even larger. Heat conduction is important in this region, despite its large size, leading to a conduction heat flux from the reaction region of the flame to the burnt gas that is sufficiently strong to cause extinction of the flame in conditions typical of the standard flammability tube. This singular feature of the flow disappears, and radiation losses cease to play a role, when the equivalence ratio is slightly increased. The effect of the radiation losses also decreases with the radius of the tube. The reaction region at the tip of a very lean flame in a narrow tube is thick and tends to be located in a region of reverse (upward) flow, which may cause flame failure without radiation losses. Kinetic effects are important at the flammability limit. However, since analysis of these effects is beyond the scope of the present work, the combustion is modeled by means of a global irreversible Arrhenius reaction. This drastic simplification prevents any accurate analysis of flame extinction but, by keeping the computations affordable, it allows to clarify the mechanism by which low gas velocities and radiation losses act upon the flame.

2. Formulation

Consider an axisymmetric flame front rising at constant speed in a very long vertical tube of radius R^* whose wall is kept at a constant temperature T_u, as in the sketch of Fig. 1. The tube is open to the atmospheric pressure at its lower end and closed at its upper end, and it is filled with a very lean fuel-air mixture of density

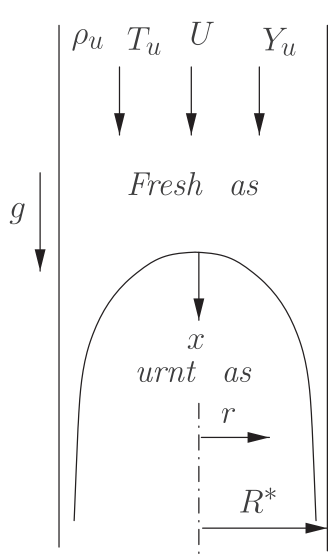

Fig. 1. Definition sketch. $R^* = 25.5$ mm for the standard flammability tube.

ρ_u, temperature T_u, and fuel mass fraction Y_u. A perfect gas with constant specific heats and mean molecular mass is assumed. Compressibility effects are left out by setting the pressure equal to a constant in the equation of state. The gas viscosity and thermal conductivity, μ and k, and the diffusivities of the fuel and the reaction products, D_i with $i = CH_4, CO_2, H_2O$ in the case of a methane flame, are taken to be powers of the temperature, of the form $\mu/\mu_u = k/k_u = \rho D_i/\rho_u D_{i_u} = (T/T_u)^\kappa$, so that the Prandtl and Lewis numbers, $Pr = \mu c_p/k$ and $Le_i = k/\rho c_p D_i$ respectively, are constant. Hereafter a subscript u denotes conditions in the fresh mixture. In what follows, $\kappa = 0.75$ and $Pr = Le_i = 1$ unless otherwise is noted. While more accurate molecular transport models are available for lean methane/air mixtures, such as the model developed by Smooke and Giovangigli [13], the simple power law model will suffice for the purposes of this work.

Combustion in the flame is modeled using a single irreversible Arrhenius reaction, $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ for methane/air, with frequency factor B and activation temperature T_a, so that the mass of fuel consumed per unit volume of gas and unit time is $w = \rho B Y_F \exp(-T_a/T)$, where ρ and T are the local gas density and temperature, and Y_F is the fuel mass fraction. Admittedly, a single-step chemistry is a poor model of the real kinetics. It cannot account for kinetic effects on flame extinction and does not allow to accurately determine the flammability limit. However, it is still useful to analyze the effects of gravity and thermal expansion, as well as the effects of preferential diffusion and radiation losses, which are the subject of this paper and seem to play an important role for near limit flames in the standard flammability tube.

The adiabatic flame temperature is $T_b = T_u + qY_u/c_p$, where q is the heat released per unit mass of fuel consumed. The dimensionless parameter $\gamma = (T_b - T_u)/T_u$ measures the thermal expansion of the gas in the flame, and the Zeldovich number $\beta = T_a(T_b - T_u)/T_b^2$ measures the temperature sensitivity of the chemical reaction. The equivalence ratio is $\phi = 17.39 Y_u/(1 - Y_u)$ for methane/air mixtures. Well-known asymptotic analysis [14] shows that, in the limit $\beta \rightarrow \infty$, the velocity and thickness of a planar adiabatic flame are

$$U_L = \frac{(2D_b B)^{1/2} Le_F}{\beta(\gamma+1)} \exp\left(-\frac{\beta}{2}\frac{\gamma+1}{\gamma}\right) \quad \text{and} \quad \delta_L = \frac{k_u}{\rho_u U_L c_p}, \tag{1}$$

where $D_b = D_F(T_b)$ and Le_F are the diffusivity and the Lewis number of the fuel.

The values of the frequency factor and the activation temperature are chosen for the single-step chemistry to give planar flame velocities in agreement with experimental results in the range of equivalence ratios of interest. For this purpose, a reference case is considered (magnitudes denoted with a subscript r) where $T_u = 300$ K and $Y_{u_r} = 0.03$, so that $\phi_r = 0.538, T_{b_r} = 1500$ K and $\gamma_r = 4$ (using $c_p = 1287$ J/kg K), and the planar flame velocity is $U_{L_r} = 4.63$ cm/s according to Ref. [15]. For each value of the activation temperature T_a, the frequency factor B is chosen for the asymptotic formula (1) to reproduce this velocity in the reference case. The value $T_a = 18,750$ K, for which $\beta_r = 10$, is then determined for the flame velocity computed numerically with the single-step chemistry to fit the experimental results of Yamaoka and Tsuji [16] for very lean mixtures, corrected to zero stretch by Wang et al. [17]. This value of the activation temperature is in line with the results of Westbrook and Dryer [18]. Figure 2 shows the computed flame velocity (solid), the velocity given by the asymptotic formula (1) (dashed) and the experimental velocity (triangles) as functions of the equivalence ratio. Also shown in this figure are the planar flame velocities determined by Wang et al. [17] from their microgravity experiments (circles) and the fits obtained with the single-step chemistry for $T_a = 37,500$ K and 52,500 K (lower and upper dotted curves), though these values will not be used in what follows.