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Heat transfer and flame stabilization of laminar premixed flames anchored to a heat-flux burner

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ABSTRACT

Measurement of the burning velocity of unstretched laminar hydrogen/air premixed flames suffers from large uncertainties owing to the highly diffusive nature of hydrogen that can give rise to flame instability. This paper reports on a numerical study of the structures and stability of laminar premixed $CH_4/O_2/CO_2$ flames and $H_2/O_2/N_2$ flames anchored to a heat-flux burner using a high-order numerical method with detailed chemical kinetic mechanisms and detailed transport properties. The aim is to elucidate the effect of the flow and temperature inhomogeneity generated by the burner plate holes on flame structures and burning velocity. Heat transfer flux between the burner plate and the surrounding gaseous mixture is investigated under various standoff distances and burner plate temperatures. The burning velocity and the detailed flow, temperature and species distributions in flames with a zero net heat flux between the flames and the burner plate are analyzed. It is found that for the methane flames, when the standoff distance is sufficiently small, the burner can essentially suppress the intrinsic flame instability, but the plate holes can give rise to flame wrinkles of the size of the holes. At high standoff distances, the non-uniformity of the flow from the burner plate holes has a minor effect on the flame surface wrinkling; however, large-scale cellular structures can appear on the flame surface due to intrinsic flame instability. For the studied methane flames the effect of non-uniformity of the flow from the burner plate holes on the burning velocity is fairly small. For the studied hydrogen flames the burner plate could not totally suppress the intrinsic flame instability. The intrinsic flame instability can give rise to a significant increase in the flame surface area and mean burning velocity, with more than 25% increase in the burning velocity.

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Introduction

A key parameter of unstretched premixed flames for various combustible mixtures is the laminar burning velocity, for which several kinds of burner systems have been developed to do experimental measurements. In general, laminar premixed flames associated with a burner are affected by the burner geometry. In certain situations, such as those of strained flat flames stabilized in counterflow burners or developing spherical flames in constant-volume enclosures, the flames are stretched. In some burner configurations and fuel/oxidizer compositions small-scale cellular shaped structures may appear on the flame surface. One may employ extrapolation methods to determine the unstretched burning velocity on the basis of that of the stretched one [1,2]. However, it is generally difficult to use extrapolation methods to correct the burning velocity of flames with small-scale wrinkling due to the cellular instability that exists.

It is highly desirable to have a flat-flame burner in order to be able to generate unstretched planar flames. Powling [3] was the first to report the use of a flat-flame burner. The principle of the method is the following: the flame is anchored to the burner by balancing the inflow velocity to the burning velocity. The latter can vary with the standoff distance between the flame and the burner. A smaller distance leads to a lower burning velocity due to the heat loss from the flame to the burner. Botha and Spalding [4] proposed a method for stabilizing the flame at a specific standoff distance by controlling the inflow velocity of the reactant mixture and the cooling rate of the burner plate. The flame is essentially non-adiabatic since there is heat loss from the flame to the burner. Due to heat loss the flame thickness increases and the ratio of density or temperature across the flame decreases. This was shown to suppress the cellular instability [5].

Theoretical analyses [6–10] and numerical simulations [11–20] of freely propagating laminar premixed flames (far from the burner) show that the hydrodynamic and diffusional-thermal mechanisms can trigger the onset of cellular flames. Thin flames with high density ratios between gases on the unburned and burned side of the flame are unconditionally unstable due to the deviation of flow streamlines across oblique flames (hydrodynamic effect [6,7]). In addition to this, fuel-lean flames with Lewis number well below unity (e.g. lean hydrogen/air flames) tend to redistribute heat and fuel/air ratio at the flame front such that the flames become increasingly cellular (diffusional-thermal effect [9,10]), whereas flames with Lewis number larger than unity tend to be pulsating [21] owing to the diffusional-thermal effect.

Previous theoretical works focused on the diffusional-thermal effects (i.e. assuming constant density in the flow field) on flame instability in porous plug burner flames with heat loss to the burners. For small wave number disturbances, Buckmaster [21] developed a dispersion relation based on a large activation energy asymptotic analysis and one-step chemistry, which reveals that the porous plug burner tends to suppress the cellular flame instability in mixtures with Lewis number less than unity whereas for mixtures with Lewis number larger than unity the burner can enhance the onset of pulsating instability when the flame is not very close to the burner plate. There is a minimum standoff distance from the flame to the burner plate within which both the cellular and pulsating instabilities can be suppressed. The recent works of Kurdyumov et al. [22,23] reveal the diffusional-thermal effect on the onset of pulsating flames near the porous plug burner; it was found that with thicker burner plate and higher density ratio the flames are easier to develop into a pulsating mode, and radiative heat loss from the flame can further promote the onset of pulsating flames and cellular flames. In previous theoretical studies heat loss from the flame to the burner plays an essential role in the flame instability. For example, the analysis of Joulin [24] indicated that the pulsating instability was a result of the time lag of the travelling temperature disturbances between the burner surface and the flame front.

In order to enable an adiabatic flame to be anchored to the burner, De Goey and his co-workers [25–27] improved a cooled flat-flame burner to a so-called heat-flux burner. The burner plate has a temperature higher than the unburned fuel/oxidizer mixture; when passing through the plate the gas mixture receives heat from the plate. By adjusting the velocity of the unburned fuel/oxidizer mixture the flame can be stabilized in the proximity of the burner, i.e. at a characteristic standoff distance from the flame to the burner surface. When the standoff distance is large the net heat transfer flux from the plate to the gas is positive, whereas if the standoff distance is small heat can be transferred from the flame to the plate, hence the net heat flux on the burner plate is a function of the standoff distance, burner plate temperature and temperature of the unburned fuel/oxidizer mixture. When the latter temperatures are prescribed, the standoff distance becomes the control parameter for the net heat flux between the burner plate and surrounding gas. In practice, the standoff distance is controlled by prescribing the mixture inflow velocity, where the net heat flux theoretically becomes zero if the gas velocity is equal to the adiabatic burning velocity.

With the heat-flux burner, previous experimental and numerical studies have shown that the flames may develop to cellular shape when the standoff distance is large [28–30]. It is unclear how the burner porosity and hole size, which could disturb the flow field in the proximity of the burner plate, would affect the onset of flame instability. Consequently, when the flame is moderately cellular, an important question is the impact of the cellular flame front on the net heat flux between the porous plate and the surrounding gas, and the implications of this on the determination of the adiabatic unstretched laminar flame speed. This has motivated the present study in which we employ a recently developed high accuracy numerical method [31] to simulate the detailed reaction zone structures and the heat transfer process, aiming at clarifying the various instability mechanisms and the burner plate effect.

Governing equations and numerical methods

Heat transfer and flame stabilization of premixed $CH_4/O_2/CO_2$ and $H_2/O_2/N_2$ mixtures passing through the porous plate of a flat-flame heat-flux burner are studied using high fidelity

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