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Effect of Lewis number on ball-like lean limit flames

Zhen Zhou [a,*], Yuriy Shoshin [a], Francisco E. Hernández-Pérez [b], Jeroen A. van Oijen [a], Laurentius P.H. de Goey [a]

[a] Department of Mechanical Engineering, Eindhoven University of Technology, P.O. Box 513, 5600MB Eindhoven, The Netherlands
[b] Clean Combustion Research Center, King Abdullah University of Science and Technology, Thuwal 23955-6900, Saudi Arabia

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ABSTRACT

The lean limit flames for three different fuel compositions premixed with air, representing three different mixture Lewis numbers, stabilized inside a tube in a downward flow are examined by experiments and numerical simulations. The CH^* chemiluminescence distribution in CH_4–air and CH_4–H_2–air flames and the OH^* chemiluminescence distribution in H_2–air flames are recorded in the experiments. Cell-like flames are observed for the CH_4–air mixture for all tested equivalence ratios. However, for CH_4–H_2–air and H_2–air flames, ball-like lean limit flames are observed. Flame temperature fields are measured using Rayleigh scattering. The experimentally observed lean limit flames are predicted qualitatively by numerical simulation with the mixture-averaged transport model and skeletal mechanism of CH_4. The results of the simulations show that the entire lean limit flames of CH_4–H_2–air and H_2–air mixtures are located inside a recirculation zone. However, for the lean limit CH_4–air flame, only the leading edge is located inside the recirculation zone. A flame structure with negative flame displacement speed is observed for the leading edges of the predicted lean limit flames with all three different fuel compositions. As compared with 1D planar flames, the fuel transport caused by convection is less significant in the present 2D lean limit flames for the three different fuel compositions. For the trailing edges of the three predicted lean limit flames, a diffusion dominated flame structure is observed.

1. Introduction

Ultra lean combustion has been considered as one of the most promising concepts for the utilization in advanced low emission and high efficiency combustion devices. Besides, hydrogen blending with hydrocarbon fuels is a potential approach for further extending the lean flammability limit and reducing emissions. However, it is a challenge to design combustors or burners which can operate near the lean limit using hydrogen-blended fuel. The combustion characteristics of hydrogen-blended fuel significantly differ from the traditional hydrocarbon fuels because addition of hydrogen reduces mixture Lewis number. Therefore, understanding of the Lewis number effect on lean limit combustion characteristics is crucial for the design of the combustors and burners operating near the lean limit conditions.

Extensive studies have been reported in the literature on the lean limit combustion characteristics. The experiments of Baker [1] in a standard flammability tube proposed by Coward and Jones [2] showed that the lean limit for upward propagating flames is lower than that for downward propagating flames due to gravity. Therefore, in order to avoid the buoyancy-induced natural convection, experimental studies on lean limit flames were conducted at micro-gravity condition. For examples, Maruta et al. [3] experimentally studied low speed counterflow premixed flames of near-limit methane-air mixtures at microgravity conditions in drop tower experiments. Qiao et al. [4,5] measured the laminar flame speed of hydrogen and methane flames with different diluents near the lean limit using the propagating spherical flame method in drop tower experiments. Zhang et al. [6] investigated the effect of pressure on counterflow methane-air flames near the lean limit in drop tower experiments.

For low Lewis number flames, so-called flame balls [7] can exist near the lean limit at micro-gravity. Zeldovich [8] first theoretically predicted the possibility of existence of a spherical and purely diffusion controlled flame which can steadily burn in an unconfined medium of premixed reactants. However, he pointed out that adiabatic flame ball solutions are unstable, and hypothesized that flame balls may be stabilized by heat loss. Ronney [7] accidentally observed flame balls in ultra lean H_2–air mixtures in a drop tower experiment. Subsequently, in parabolic flight experiments, Ronney

* Corresponding author.
E-mail addresses: Z.Zhou1@tue.nl, paizhouyu@gmail.com (Z. Zhou).

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et al. [9,10] confirmed that flame balls can exist in other different near-limit low Lewis number mixtures. Furthermore, in space shuttle experiments, Ronney et al. [10] found that flame balls drifted away from each other. Buckmaster et al. [11] found that flame balls can be stabilized by radiative heat loss. Minaev et al. [12] further theoretically predicted that flame balls are self-drifting. Recently, Takase et al. [13] observed that a ball-like low Lewis number flame exists near the lean limit in a convective flow at micro-gravity. Fursenko et al. [14,15] experimentally and numerically observed multiple ball-like lean limit flames in a low speed counterflow burner at micro-gravity conditions.

Although steady flame balls were considered non-existent at normal gravity conditions, a transition from cell-like propagating flames to ball-like propagating flames in H_2–CH_4–air mixtures was observed by Shoshin and de Goey [16] in experiments on flame propagation in a tube under normal gravity condition. Shoshin et al. [17] further studied this ball-like lean limit flame by experiments and numerical simulations, and found that the temperature profile along the centerline for the ball-like flame is very similar to that of the so-called travelling flame ball [18–20]. Subsequently, a ball-like lean limit flame was stabilized in a downward flow of premixed reactants [21]. A detailed comparison between experimental ball-like flames and numerical ball-like flames has been conducted by Hernández-Pérez et al. [22]. Despite the achievements of above studies, the effects of different fuel Lewis numbers on the lean limit flames in a tube remain unknown. Studies on lean limit flames in a tube for mixtures with different Lewis numbers can improve the understanding of the influence of Lewis number on the lean limit combustion properties and mechanisms which determine the lean flammability limit. In this regard, the aims of the present study are as follows:

1. To experimentally study the influence of fuel Lewis number on the structure of a lean limit flame stabilized in a tube in a downward flow of premixed reactants.
2. To examine the fuel Lewis number effect on the lean limit flame structure by numerical simulations.
3. To investigate the differences between the lean limit flames stabilized inside a tube at normal gravity with 1D planar lean limit flames and 1D micro-gravity flame balls.

In the present study, pure CH_4, pure H_2, and a mixture of 40% H_2 and 60% CH_4 (specified on a molar basis) are selected as the fuels, and air as oxidiser, to prepare lean mixtures with different Lewis numbers. In the following sections, the experimental setup and numerical approach are presented, and the experimental and numerical results are discussed. Finally, concluding remarks are given.

2. Experimental setup

A schematic of the experimental setup is shown in Fig. 1. As described in the following section, line-wise Rayleigh scattering measurements have been performed along a line normal to the tube symmetry axis. In order to measure the temperature field of the whole flame, a burner is designed which allows traversing steadily the burning flame inside the tube through the measurement section. The burner consists of a hollow piston and a quartz tube with an inner diameter of 13.5 mm and a length of 100 mm. A linear motor is connected to the piston, which moves the piston inside the tube with a constant speed. A perforated plate with thickness of 2 mm and holes of 0.4 mm diameter uniformly spaced with 0.5 mm pitch is mounted in the outlet of the piston to generate a uniform outlet flow profile. The slit between the piston and the tube is sealed by Teflon tape. Cylinder gases (H_2, CH_4 and synthetic air-21% O_2) with 99.9% purity are used in the experiments. The supply of H_2, CH_4 and synthetic air is controlled by mass flow controllers with an uncertainty less than 1%. The estimated uncertainty of experimental equivalence ratio caused by mass flow controllers is 2%. Small fluctuations of mixtures composition (within 1% error), caused by inherent small flow instabilities introduced by mass flow controllers are damped by a buffer mounted in the gas line before the mixture is supplied to the burner. The mixture is ignited at the bottom of the burner using a household lighter at a sufficiently large equivalence ratio. After ignition, the equivalence ratio is slowly reduced and near-limit flames are stabilized at some distance from the perforated plate. The inlet mixture velocity is set close to the blow-off value for lean limit flames (determined in separate experiments). The temperature of the tube wall is kept nearly at room temperature by supplying cooling air to the outside of the quartz tube. The tube wall temperature is monitored by a pyrometer Pyrospot DT 40L.

Table 1
Summary of conditions for the experiments with different equivalence ratios. * Mole fraction linearly weighted average based effective Lewis number for CH_4 and H_2 mixture.

Condition	Fuel	Fuel Lewis number (*Le*)	V_{in} (cm/s)
I	CH_4	0.97	0.58
II	40% H_2 + 60% CH_4	0.7*	0.72
III	H_2	0.296	0.73

Flame chemiluminescence is recorded at a fixed piston position with a distance of 30 mm from the outlet of the tube. An AVT-PIKE F-032b CCD-camera equipped with an interference filter (430 nm and bandwidth 10 nm) and an intensified CCD camera (Princeton Instruments ICCD) mounted with an interference filter (307 nm and bandwidth 10 nm) are employed to record the CH* and OH* chemiluminescence for the CH_4 contained flames and H_2 flames, respectively. The chemiluminescence images represent a line-of-sight integrated emission intensity. The in-plane radial emission intensity distributions are recovered by Abel inversion of the recorded horizontal intensity profiles. The conditions of the experiments are listed in Table 1. Only fuel Lewis numbers less than unity are considered in the present study, because flame balls form only for below unit Lewis number mixtures. It can be seen in Table 1 that the effective fuel Lewis number decreases significantly from condition I to condition III. The details for the Rayleigh scattering temperature measurement are described in the next section.

3. Rayleigh temperature measurement

A blue CW laser with an output power of 1 W operated at 450 nm is used for the measurements. In order to avoid strong background scattering when the laser beam passes through the tube wall, two symmetrical holes with a diameter of 2 mm are drilled in the middle of the tube. Two metal tubes with an inner diameter of 6 mm are horizontally attached to the tube wall sharing the co-axis with both small holes. At the inlet side of the laser beam, the metal tube is fitted with an anti-reflection window, while a Brewster window is mounted to the outlet side of the laser beam. This combination allows to minimize forward scattering from the front window and reflection from the back window, minimizing thereby the background signal related to the stray light. To further reduce background radiation, the inner metal tube wall and half of the inner quartz tube wall are painted with black high-temperature paint. The laser beam is focused in the center of the tube with a 15 mm focal length lens, procuring a nearly constant width beam of approximately 0.3 mm diameter inside the quartz tube. A flame inside the tube is scanned by moving the piston with a constant speed of 0.7 mm/s. The scattered light from the laser beam inside the tube is recorded by the AVT-PIKE