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Laminar burning velocities and Markstein lengths of premixed methane/air flames near the lean flammability limit in microgravity

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ABSTRACT

Effects of flame stretch on the laminar burning velocities of near-limit fuel-lean methane/air flames have been studied experimentally using a microgravity environment to minimize the complications of buoyancy. Outwardly propagating spherical flames were employed to assess the sensitivities of the laminar burning velocity to flame stretch, represented by Markstein lengths, and the fundamental laminar burning velocities of unstretched flames. Resulting data were reported for methane/air mixtures at ambient temperature and pressure, over the specific range of equivalence ratio that extended from 0.512 (the microgravity flammability limit found in the combustion chamber) to 0.601. Present measurements of unstretched laminar burning velocities were in good agreement with the unique existing microgravity data set at all measured equivalence ratios. Most of previous 1-g experiments using a variety of experimental techniques, however, appeared to give significantly higher burning velocities than the microgravity results. Furthermore, the burning velocities predicted by three chemical reaction mechanisms, which have been tuned primarily under off-limit conditions, were also considerably higher than the present experimental data. Additional results of the present investigation were derived for the overall activation energy and corresponding Zeldovich numbers, and the variation of the global flame Lewis numbers with equivalence ratio. The implications of these results were discussed.

1. Introduction

The laminar burning velocity is one of the fundamental properties of a reacting premixed mixture, and its reliable data are constantly needed for combustion applications. Since the late 1970s, there have evolved significant advances to understand the effects of flame stretch on the laminar burning velocity. Failure to account for the stretch effects may well explain the large spread in reported burning velocity values from earlier investigations [1,2]. So far, several techniques for measuring the one-dimensional laminar burning velocity have been used, and for a wide range of temperature, pressure, and fuel rather accurate measurements have been obtained by employing flat or curved flames in stagnation flow (e.g., [3–7]), propagating spherical flames in combustion vessel (e.g., [8–12]), or flat flames stabilized on burner [13,14]. With all those measurement techniques proper care could be taken to remove the effect of flame stretch either during experimentation or through further data processing.

For the laminar burning velocity of methane/air mixtures, a substantial improvement in consistency among the measurements was achieved in recent years due to the recognition of the influence of flame stretch and the resulting corrections for it [10,14]. For example, for the stoichiometric CH_4/air flame, recent experiments converge toward a value around 36 cm/s, and the differences between the results of different measurement techniques do not vary by more than roughly 1 cm/s [14]. However, at lower and higher equivalence ratios there is still noticeable variation among burning velocity data from various sources. The situation is even less satisfactory for very lean and very rich flames since the scatter tends to widen as the limits of flammability are approached. Particularly, few measurements have been performed for the weakly-burning near-limit mixtures.

Part of the difficulty stems from the fact that, when the flames are weaker, they become more sensitive to experimental errors. However, a major complicating factor is the influence of gravitational effects. For weakly-burning near-limit mixtures, flames at earth gravity (i.e., 1-g) become greatly affected by buoyant distortion because the gas speed driven by natural convection is of the same order as the burning velocity. The problem of this type has been consistently observed during previous experiments and was stressed in reviews of microgravity combustion [15–17]. The gen-

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Nomenclature

E	activation energy	u_L	stretched laminar burning velocity
I	correction factor, as defined	u_g	gas velocity induced by flame expansion
Ka	Karlovitz number	u_{L0}	unstretched laminar burning velocity
L, L_b, L_r	Markstein lengths, as defined	$u_{L0,\,lim}$	u_{L0} at flammability limit
Le	Lewis number	V	volume encircled by flame front
Ma	Markstein number	Ze	Zeldovich number
n	mole ratio	α	total stretch rate
R	universal gas constant	α_c	stretch rate due to flame curvature
r	radius	α_s	stretch rate due to strain
r_{sch}	schlieren flame front radius	ϕ	fuel-equivalence ratio
r_u	cold flame front radius	ρ_b	density of burned gas
S	stretched flame speed	$\overline{\rho_b}$	mean density of gas within flame front r_u
S_0	unstretched flame speed	ρ_u	density of unburned mixture
t	time	δ	flame thickness
T_{ad}	adiabatic flame temperature	δ_0	characteristic thickness of one-dimensional flame
T_b	burned gas temperature	δ_L	characteristic laminar flame thickness given by $\delta_L = \nu/u_{L0}$
T_r	temperature at radius r	ν	kinematic viscosity of unburned mixture
T_u	unburned mixture temperature		

eral cognition is that conducting experiments under microgravity conditions is essential for eliminating the complications of buoyancy and thus enabling reliable measurements of near-limit flame properties. In fact, the behaviors of CH_4/air flames near lean limit have been examined by several experimental investigations in microgravity [18–23]. Most of those studies were concerned with flame extinction phenomena and flammability limits, while the burning velocities of near-limit flames have not received much attention. One exception is the study of Ronney and Wachman [20], in which lean limit compositions and near-limit values of the burning velocity were determined for CH_4/air mixtures utilizing outwardly propagating spherical flames in a cylindrical vessel; those authors have also inferred the near-limit burning velocities for the microgravity experiments of Strehlow and Reuss [18], in which corresponding flame propagation speeds were measured for lean CH_4/air mixtures using a standard flammability tube; nevertheless, the effects of flame stretch were not considered, while the reported burning velocities were for stretched flames.

In view of the above considerations, the main objective of the present study is to determine the laminar burning velocities and the sensitivities of the flame response to stretch for near-limit lean CH_4/air flames. Using a microgravity environment, weakly burning CH_4/air flames having fuel-equivalence ratios in a range of 0.512–0.601 are studied at ambient initial temperature and pressure. Outwardly propagating spherical flames are employed to measure flame speeds, from which corresponding stretched and unstretched laminar burning velocities are derived. Associated Markstein lengths are obtained to express the effects of flame stretch on the burning velocities. Also extracted are the activation energy and Zeldovich numbers representing the sensitivity of chemical reactions to flame temperature, and the global flame Lewis numbers. Measured unstretched laminar burning velocities are compared with those from a numerical prediction utilizing the one-dimensional flame model with a full kinetic mechanism. Where data are available, present results are compared with those of other studies.

2. Experimental

2.1. Apparatus

The experimental package consisted of a closed combustion chamber, spark generator, high-speed schlieren system, video camera, and pressure measurement system. The package was mounted in a steel framework and used for all 1-g and microgravity tests.

The 80-mm-inner-length, cubic, stainless steel combustion chamber could be operated over a pressure range extending from vacuum to a maximum of 15 bar. Optical access was provided by two 80 mm length square quartz windows mounted opposite one another. Reactant mixtures were prepared within a sealed separated vessel by blending methane and air at appropriate flow rates controlled with mass flow controllers (Alicat Scientific, type MC). Accuracy of the mixture composition was estimated to be ±0.02% in the listed values in Table 1. The combustion chamber was exhausted prior to filling it with the prepared reactant mixture to reach a pressure slightly higher than the ambient pressure (i.e., 1 atm). The exhausting and filling procedure was repeated for five times to ensure that the chamber would be indeed filled with the specified mixture. After the mixture filling operation was complete, a vent valve on the chamber was opened manually for several seconds to balance pressure inside the chamber and ambient pressure. Methane/air mixtures were studied at a constant temperature of 298 ± 2 K for fuel-equivalence ratios between 0.512 and 0.601 (corresponding fuel concentrations between 5.09% and 5.92%). The lowest equivalence ratio of 0.512 is the lean flammability limit of methane in air that was found from the present microgravity tests.

The mixture was ignited by a spark at the center of the chamber using two electrodes extending from the bottom and one side wall. The flame propagation was observed with the high-speed schlieren photography system. Flame pictures were recorded using a high-speed digital video camera (Redlake MotionScope M1) at 500 frames per second. Additionally, the pressure history in the chamber, which could be correlated with the flame propagation records, was measured by using a membrane type strain-gauge transducer located at the bottom of the chamber.

Microgravity experiments were performed in the free-fall facility at the combustion laboratory of the Technical University of Lodz, Poland. In this facility (see [24] and [25] for a detailed description), the experimental package experiences 1.2 s of 10^{-3}–10^{-2} g reduced gravity. Immediately prior to the release of the package, the high-speed video camera was triggered and a computer began to record the signal from the pressure transducer. As the package was released, a timer was triggered. After a short delay to allow oscillations from the release to decay, a timer pulse trig-