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A computational study of low oxygen flammability limit for thick solid slabs

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Abstract

A preventive approach to fire safety is proper material selection based on the flammability characteristics. One such measure of flammability is the limiting oxygen index (LOI). This is a commonly used numerical flammability index for relative grading and selecting materials. The test measures the extinction limit of a downward spreading flame over a finite size (rectangular slab or rod) fuel specimen. In this work, a two-dimensional numerical model was used to study the flame stabilization and extinction characteristics over a thick model solid fuel, which resembles a specimen burning near extinction limit in an LOI testing procedure. The computations were preformed for a mixed buoyant-forced-flow environment prevailing in the LOI test at normal gravity. At sufficiently high oxygen level (far away from flame extinction limit) the flame is anchored on the sides of the fuel slab (side-stabilized flame), but as the oxygen level is reduced, at a certain value the flame stabilization point abruptly shifts from the sides of the specimen to the wake region (wake flame). The structural details of these two modes of flame stabilization are discussed. The computations also show that the shift in the flame-anchoring position with oxygen level exhibits hysteresis; i.e., multiple flame solutions may exist for a given environmental condition of flow and oxygen. The flame extinction limits and flame-shift limits (side-stabilized flame to wake flame and vice versa) in ambient oxygen percentage are presented for different forced-flow velocities. Over the velocity range studied here, the side-stabilized flame (similar to flames over of thin fuels) becomes less flammable (higher LOI) at higher velocity, whereas the wake-stabilized flame becomes more flammable (lower LOI) with increase in forced-flow velocity. To understand the implication of this earth-based measurement to material selection for space application, additional computations were performed for pure forced-flow environment in zero gravity. Stabilization and extinction behavior of the flames at normal gravity are compared with those in zero gravity. The computations in a pure forced-flow environment show that the two modes are also present in a zero-gravity environment but only above certain minimum flow velocity. Below this velocity only the single flaming solution was obtained. In the present computations, the LOI values at zero gravity were lower than those at normal gravity. For zero gravity the LOI based on side-stabilized flame (for thin fuels) shows a nonmonotonic behavior: there is a minimum LOI which for the present set of property and kinetic parameter values occurs at a forced velocity of about 3–5 cm/s. For zero gravity the LOI based on wake flame extinction decreases rapidly with flow velocity for small velocities but with further increase in velocity the LOI value stays approximately constant.

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1. Introduction

The limiting oxygen index (LOI) is commonly used as one of the numerical measure of the flammability of solids. It is defined as the minimum level of oxygen (expressed in volume percentage) in a flowing homogeneous mixture of oxygen and nitrogen that will barely support combustion of the material in downward spreading mode (candle-like). Experimentally, the LOI is determined by following specific test procedures described in various equivalent test standards (e.g., ASTM D2863, BS2782 PART 141, etc.).

The specimens used in the tests are generally thick (thin film-type specimen can also be used) in the form of rods and bars. A specimen is mounted vertically on a specimen holder and ignited at the top in normal gravity and in an imposed-forced flow (3–5 cm/s, in ASTM D2863) of known oxygen and nitrogen composition. The top of the specimen is engulfed in the flame while the flame front spreads downward around the exterior. Sibulkin and Little [1] and Halli and T'ien [2] have reported their observations of burning phenomenon for downward flame spread over cylindrical PMMA rods where a conical fuel shape formed underneath the flame. As the oxygen level in the flowing gas mixture was reduced, the flame front, which normally anchors on the sides of the fuel (side-stabilized flame), moved back (downstream) relative to the pyrolysis front. The flame-spread rate decreased and the conical surface flattened. The retreated flame remained in the wake region (i.e., a wake flame) behind the flattened top end of the specimen (if given sufficient experimental time) and eventually extinguished as a wake flame upon further reduction in oxygen level. Fig. 1A shows the flame stabilization and the solid specimen shape as described above in a typical LOI testing procedure.

Early LOI studies by Finemore and Martin [3] showed that an LOI would be fairly constant within the velocity range 3–12 cm/s, a conclusion which was later questioned by several investigators [4–7]. Wharton [5] reports several previous investigations on the subject: while some found LOI values to increase nonlinearly with an increase in gas flow velocity, others reported little or no dependence of LOI on gas flow velocity. Wharton [5,6] tried to resolve this discrepancy. He reported that ambient air could enter the column under certain conditions of small gas inlet velocity and alter the inlet gas composition and hence the LOI value, but at high velocity where there is no entrained ambient air, the LOI is independent of velocity. McIlhagger and Hill [8] conducted a study on thin polypropylene films where LOI showed an upward trend with increase in volumetric flow rate of the gas. The LOI first increased and then remained approximately constant at higher flow rates. Further, Zhevlakov et al. [7] described their LOI-like device for PMMA and fiberglass-reinforced polymer specimens of cross section 0.2 × 0.3 cm and length 15–20 cm. Their observation of flame stabilization was similar to that of Refs. [1,2]. In their work they defined the LOI as the oxygen level where the flame stopped propagating along the side surface (i.e., the transition limit to wake flame). From 0 to 6 m/s their LOI value increased with increasing forced-flow velocity.

Some of the above-noted observations suggest that flame extinction mechanism for thick fuel specimens may be different from that for thin film-type specimens. For the thicker fuel specimen the flame can stabilize in the wake region; however, for thin specimens the flame is always anchored on the sides. Therefore, one of the objectives of this work is to study the effect of imposed-flow velocity on flame stabilization and extinction of the two modes of flames, namely the side-stabilized flame and the wake flame. The other objective of this study is to investigate the effect of gravity on flame stabilization and extinction phenomena. All previous LOI experiments have been done in normal earth gravity, but the LOI values and trends may not be the same in a zero-gravity environment. Therefore, an assessment of the effect of gravity on LOI is necessary to understand the effectiveness/limitation of these earth-based tests for determining the flammability of material for space application.

These objectives are accomplished by studying a numerical model where a nonspreading flame is stabilized over a two-dimensional (thick), nonregressing solid slab in a mixed-flow environment of gravity and forced flow. Fig. 1B shows the schematic of the model problem showing that the flame is anchored at top of the rectangular fuel specimen. The gravity vector acts downward and the forced flow with upstream velocity U_∞ is imposed from the bottom and is directed upward. This configuration approximates a realistic situation with small burning rate, near the extinction limit. The specimen considered here is a 1.0 cm (wide) × 10.5 cm (long) slab. In this model fuel sample, the upper 0.5 cm (l_p) is the fuel vapor source (including both side surfaces and