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Solid combustion research in microgravity as a basis of fire safety in space

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Abstract

This paper introduces fire safety standards for flammability evaluation of solid material intended for use in a spacecraft habitat. Two types of existing standards include material evaluation by pass/fail criteria corresponding to Test 1 of NASA STD 6001B and evaluation by a flammability index such as maximum oxygen concentration (MOC) corresponding to the improved Test 1. The advantage of the latter is the wide applicability of the MOC index to different atmospheres in spacecraft. Additionally, the limiting oxygen index (LOI) method is introduced as a potential alternative index for the evaluation using the improved Test 1 method. When criteria based on an index such as MOC or LOI are applied for material screening, the discrepancy of the index to the actual flammability limit in microgravity such as minimum limiting oxygen concentration (MLOC) is essential information for guaranteeing fire safety in space because material flammability can be higher in microgravity. In this paper, the existing research on the effects of significant parameters on material flammability in microgravity are introduced, and the difference between the limiting value in microgravity and the indices given by the standard test methods on the ground is discussed. Finally, on-going efforts to develop estimation methods of material flammability in microgravity according to normal gravity tests are summarized.

Keywords: Fire safety in space; Flame spread; Extinction limit; International standard; Electric wire

Abbreviations: LOC, Limiting oxygen concentration, Minimum oxygen concentration in which a spreading flame is sustained for a given condition (sample thickness, flow velocity, pressure, and so on) other than oxygen concentration; MLOC, Minimum limiting oxygen concentration, Minimum LOC in a wide range of external flow velocity including both opposed and concurrent flow fields under microgravity. This value is determined for a given material and sample thickness under the pressure condition in a spacecraft; MOC, Maximum oxygen concentration, Oxygen concentration in which all tested samples pass Test 1 [14] defined for upward flame spread; ULOI, Upward limiting oxygen index, Oxygen concentration in which 50% of the tested samples pass Test 1 [14] defined for upward flame spread; LOI, Limiting oxygen index, LOC under the condition specified by ISO 4589-2 [20] defined for downward flame spread.

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1. Introduction

Fire safety is one of the most sensitive issues in manned space missions. At the very early stages of space flight development, oxygen concentration in spacecrafts was almost 100%, and combustible materials present in the spacecraft were flammable under such oxygen concentration, which resulted in high risk of fire. At present, the oxygen concentration in spacecraft is much less, such as 21% in the International Space Station (ISS), and materials intended for use in spacecraft are approved by NASA's fire safety standard STD-6001B (originally NHB 8060.1C) [1,2]. The test method is essentially a pass/fail test in which upward flame spread over a material is observed under ambient conditions to which the material is exposed in the spacecraft. If the material passes the test, it is allowed into the spacecraft cabin.

A drawback of such pass/fail tests is that their results are applicable only to the same conditions as those in the test, and it does not provide further information on the actual flammability of the material under the spacecraft conditions. If the test provides information on limiting flammability values of the material, the test results can be used as design data for other space activities. Even if the oxygen concentration in the spacecraft changes, the user does not have to repeat the same material evaluation tests for those conditions. Actually, oxygen concentration in pre-extravehicular activity (EVA) or in future spacecraft can be higher than that in the present ISS. Under the present fire safety protocol based on NASA STD 6001B, all tests for spacecraft material need to be retested under the worst conditions if the cabin air condition changes. Considering such disadvantages, NASA recently introduced the concepts of upward limiting oxygen index (ULOI) and maximum oxygen concentration (MOC) based on the test method of NASA STD 6001B. ULOI and MOC, which will be explained in detail in the next section, refer to the oxygen concentrations at which almost half of the samples of a material pass the test and all samples pass the test, respectively.

Although ULOI and MOC are useful concepts it is unclear how these indices work in microgravity. In such an environment, natural convection does not occur, and very low flow velocity can be present due to the HVAC system or movement by the astronauts. Moreover, combustion products remain around the area where combustion took place. Such differences cause changes in material flammability. Therefore, the difference between the maximum flammability limit in microgravity and the indices such as ULOI or MOC must be determined so that the indices taken in 1G can be effective for evaluating the risk of fire in microgravity even when the designed air conditions in spacecraft change. Moreover, the effects of many experimental parameters such as external flow velocity, material thickness, type of material, external heating and ambient pressure should also be considered. However, obtaining such results can be extremely difficult because quantitative data on the parameters are necessary for the use of indices as criteria to evaluate material fire safety in space. The author believes the combustion community is the appropriate group to address such issues, because a scientific understanding on material flammability is the crucial element to address them. In this paper, the latest research on the individual parameters is reviewed, and the necessary information to be added to the body of knowledge in this field is discussed. Although some excellent review papers already exist on microgravity combustion [3–5], fire safety technology in space [6–10] and fire research [11], those focusing on the fire safety standards for space applications under the aspect of combustion fundamentals are limited. The present study summarizes the standard test methods for material flammability evaluation and existing research relating to material flammability in microgravity.

2. Fire safety standard

2.1. Test 1 and Test 4 in NASA STD 6001B

In this section, two standard test methods of material flammability evaluation, NASA-STD-6001B and the LOI method, are introduced. As previously mentioned, differences in the indices

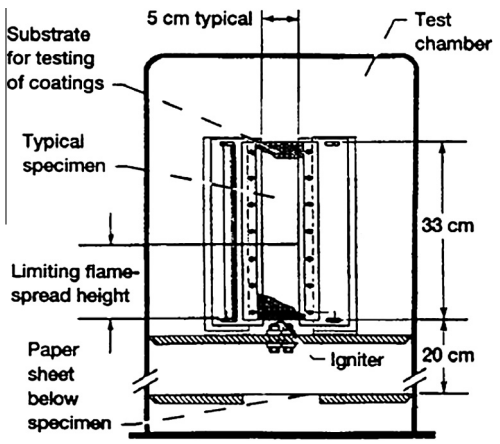

Fig. 1. Experimental configuration for the upward flame propagation test (Test 1) of NASA-STD-6001B [12]. The active area of the test sample is typically 5 cm × 33 cm. A chemical igniter is placed at the bottom of the sample. (From" A Research Plan for Fire Prevention, Detection, and Suppression in Crewed Exploration Systems" by A.G. Ruff, L.D. Urban, K.M. King [9]; reprinted by permission of the American Institute of Aeronautics and Astronautics, Inc.").