A New Test Method For Material Flammability Assessment in Microgravity & Extraterrestrial Environments

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The standard oxygen consumption (cone) calorimeter (described in ASTM E 1354 and NASA STD 6001 Test 2) is modified to provide a bench-scale test environment that simulates the low velocity buoyant or ventilation flow generated by or around a burning surface in a spacecraft or extraterrestrial gravity level. The Equivalent Low Stretch Apparatus (ELSA) uses an inverted cone geometry with the sample burning in a ceiling fire (stagnation flow) configuration.

For a fixed radiant flux, ignition delay times for characterization material PMMA are shown to decrease by a factor of three at low stretch, demonstrating that ignition delay times determined from normal cone tests significantly underestimate the risk in microgravity.

The critical heat flux for ignition is found to be lowered at low stretch as the convective cooling is reduced. At the limit of no stretch, any heat flux that exceeds the surface radiative loss at the surface ignition temperature is sufficient for ignition.

Regression rates for PMMA increase with heat flux and stretch rate, but regression rates are much more sensitive to heat flux at the low stretch rates, where a modest increase in heat flux of 25 kW/m^2 increases the burning rates by an order of magnitude.

The global equivalence ratio of these flames is very fuel rich, and the quantity of CO produced in this configuration is significantly higher than standard cone tests.

These results [2] demonstrate the ELSA apparatus allows us to conduct normal gravity experiments that accurately and quantifiably evaluate a material's flammability characteristics in the real-use environment of spacecraft or extra-terrestrial gravitational acceleration. These results also demonstrate that current NASA STD 6001 Test 2 (standard cone) is not conservative since it evaluates materials flammability with a much higher inherent buoyant convective flow.

A Better Test Method is Needed

NASA's current method of material screening determines fire resistance under conditions representing a worst-case for normal gravity flammability - the Upward Flame Propagation Test (Test 1[1]). The applicability of Test 1 to fires in microgravity and extraterrestrial environments, however, is uncertain because the relationship between this buoyancy-dominated test and actual extraterrestrial fire hazards is not understood.

Unlike Test 1, the NASA STD 6001 Test 2 [1] standard oxygen consumption (cone) calorimeter (also described in ASTM E 1354) provides quantitative data on ignition delay times and burning rates of materials. However, it currently lacks any pass-fail criteria. In addition, it too is buoyancy-dominated.

The objective of this research is to modify the well-instrumented standard cone configuration to provide a reproducible bench-scale test environment that simulates the buoyant or ventilation flow that would be generated by or around a burning surface in a spacecraft or extraterrestrial gravity level. We will then develop a standard test method with pass-fail criteria for future use in spacecraft materials flammability screening. (For example, dripping of molten material will be an automatic fail.)

Scaling Arguments

The ELSA concept is based upon scaling analysis that demonstrates buoyant stretch and forced stretch can be equated. This means that through scaling we can burn materials over a wide range of gravity levels.

Equivalent stretch rates can be determined as a function of gravity, imposed flow, and geometry. For purely buoyant stagnation flow, the equivalent stretch rate is $a_b = [(\rho_e-\rho^*)/\rho_e][g/R]^{1/2}$ [6,7], where the density difference from the average flame temperature to ambient is used, g is gravity, and R is the radius of curvature of the sample. For purely forced flow, the equivalent stretch rate is characterized by either $a_f = 2U_\infty R$ for a cylinder[6], or $a_f=U_{jet}/d_{jet}$ for a jet impinging on a planar surface[9]. U_∞ is the velocity of the ambient stream or the jet, R is the radius of curvature of the cylinder, and d_{jet} is the diameter of the jet. A generalized expression for stretch rate which captures mixed convection includes both buoyant and forced stretch is defined[6] as $a_{equivalent} = a_f(1+ a_b^2/a_f^2)^{1/2}$. The inherent buoyant stretch for the current ELSA holder is ~4 s^{-1} based on a correlation of regression rates for cylinders and flat disks. This correlation also allows us to determine that the normal cone buoyant stretch rate is 33 s^{-1}] by extrapolating the correlation to the 'ideal' burning rate (heat flux from flame to surface only) for clear PMMA from [11].

The stretch rate is simply the velocity gradient as the flow decelerates toward the fuel surface. The velocity gradient for flame spread problems has been shown to be the important flow parameter [Wichman, 1983], and the flame is spreading deep within the boundary layer where the velocity gradient is almost constant. For forced flow velocities of up to 20 cm/s (spacecraft ventilation), the velocity gradient (stretch rate) is of the same order for small fires. Thus a test method which varies the velocity gradient (stretch rate) will capture the essential flammability behavior of flame spread as well as stagnation point fires.

To demonstrate this scaling with experimental results, the ignition delay results of FIST [4] at different flow rates, including natural convection, are added to the ignition delay –stretch plot by estimating the Blasius boundary layer velocity gradient at the surface for the free stream flow based on their experiment geometry. The correlation holds up very well over a wide range of velocity gradient in cm/s per cm (flame stretch rate, s^{-1}). While the normal cone flow field is not well characterized, the flame is stabilized near a surface with a cross flow (entrained air), and velocity gradients in a laminar boundary layer near the surface are constant. For a 5 cm surface (1/2 sample) with an average velocity gradient near the surface of 33 s^{-1}, the average entrained cross flow would be ~20 cm/s, which is reasonable.

References

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