An Earth-Based Equivalent Low Stretch Apparatus to Assess Material Flammability for Microgravity & Extraterrestrial Fire-Safety Applications

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Abstract

One of the performance goals for NASA's enterprise of Human Exploration and Development of Space (HEDS) is to develop methods, data bases, and validating tests for material flammability characterization, hazard reduction, and fire detection/suppression strategies for spacecraft and extraterrestrial habitats. This work addresses these needs by applying the fundamental knowledge gained from low stretch experiments to the development of a normal gravity low stretch material flammability test method. The concept of the apparatus being developed uses the low stretch geometry [1] to simulate the conditions of the extraterrestrial environment through proper scaling of the sample dimensions to reduce the buoyant stretch in normal gravity. The apparatus uses controlled forced-air flow to augment the low stretch to levels which simulate Lunar or Martian gravity levels. In addition, the effect of imposed radiant heat flux on material flammability can be studied with the cone heater. After breadboard testing, the apparatus will be integrated into NASA's White Sands Test Facility's Atmosphere-Controlled Cone Calorimeter for evaluation as a new materials screening test method.

Applicability of the NASA's Upward Flammability Test

NASA's current methods of material screening determine fire resistance under conditions presenting a worst-case for normal gravity flammability- the upward flammability Test 1. The applicability of these Test 1 conditions to fires in microgravity and extraterrestrial environments, however, is uncertain because the relationship between these buoyancy-dominated tests and actual extraterrestrial fire hazards is not fully understood. Flames in microgravity are known to preferentially spread upwind [2], not downwind as in the normal gravity upward flammability screening Test 1. At low velocity flow, the Test 1 type flame spread was not viable over solid cylinders, as shown in Figure 1. However, the stagnation point flame at the tip of the cylinder (low stretch flame) was viable [3]. In addition, the maximum flammability in the upwind spread configuration is known to be at lower imposed flows and lower oxygen concentrations than occur in normal gravity [4].

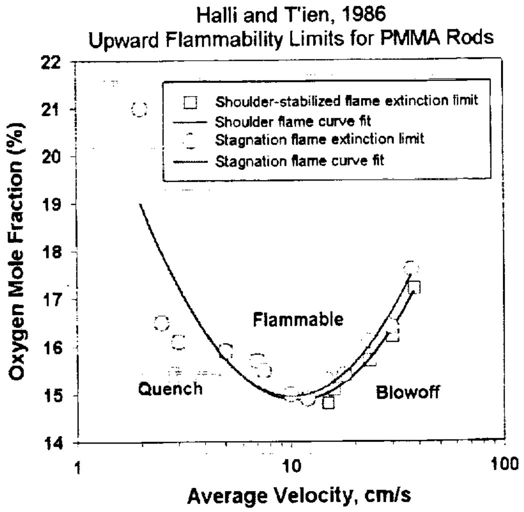

Figure 1: Upward flammability limits for flame spread along PMMA rods.

Theoretical Foundation

Theoretical predictions by Foutch and T'ien (1987)[1], shown in Figure 2, indicate that it is possible to understand a material's burning characteristics in the low stretch environment of spacecraft (Fr=0, non-buoyant, but with some movement induced by fans and crew disturbances) by understanding its burning characteristics in an equivalent Earth-based stretch environment (Fr=∞, induced by normal gravity buoyancy). Similarly, Earth-based stretch environments can be made equivalent to those in Lunar- and Martian-surface stretch environments (which would induce partial-gravity buoyancy).

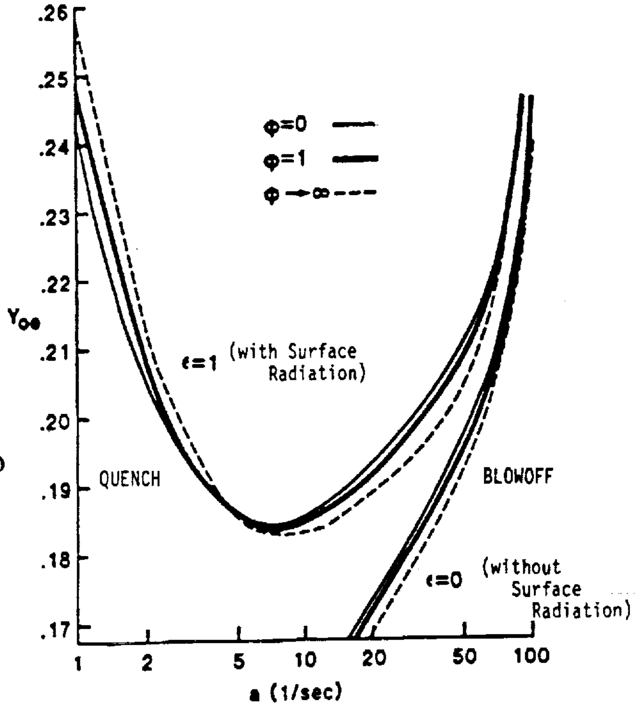

Figure 2: Extinction boundary as a function of ambient oxygen and forced (0), buoyant (∞), and mixed (1) convective stretch.

Equivalent Low Stretch Scaling

Equivalent stretch rates can be determined as a function of gravity, imposed flow, and geometry. For purely buoyant flow, the equivalent stretch rate is $a_b = [(\rho_e-\rho^*)/\rho_e]\,[g/R]^{1/2}$ [1,5]. For purely forced flow, the equivalent stretch rate is characterized by either $a_f = 2U_\infty/R$ for a cylinder[5], or $a_f=U_{jet}/d_{jet}$ for a jet impinging on a planar surface[6]. A generalized expression for stretch rate which captures mixed convection includes both buoyant and forced stretch is defined[5] as $a_{mixed} = a_f(1+ a_b^2/a_f^2)^{1/2}$. In the normal gravity experiments to date, the buoyant stretch is varied through R, the radius of curvature, but the buoyant stretch could also be varied through g, the gravity level. In this way the effect of partial gravity, such as those found on the Moon (1/6 g) or Mars (1/3 g) can be captured in the definition of flame stretch.

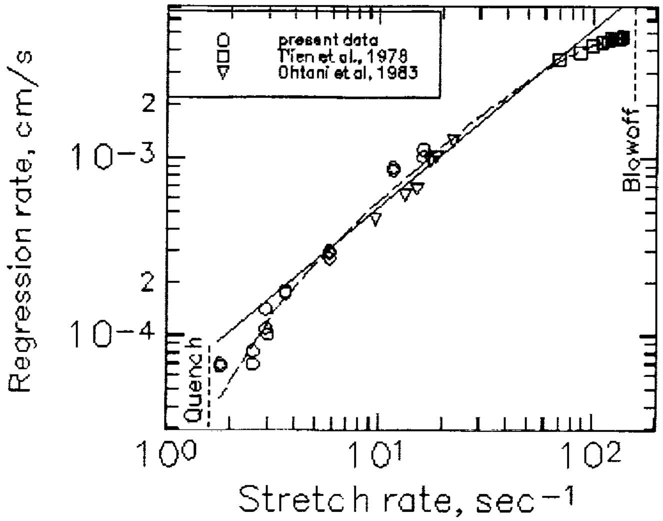

Figure 3: PMMA regression rates over the range of flammability in air.

Normal Gravity Low Stretch Results

Recent experimental results [1], shown in Figure 3, demonstrate the transition from a robust flame at stretch rates of 10-20 s^{-1} to a quenched flame at very low stretch in the 21% oxygen environment tested.

Figure 3 captures the surface regression rates for PMMA over the full range of flammability in air, from blowoff at high stretch, to quenching at low stretch, observed for the first time in the above-mention experiments, which are represented by the data circles. Previous higher stretch results are represented by the squares and triangles. The solid line drawn through the central portion of the data ($3<a<100\ s^{-1}$) has a slope of unity, which indicates regression is proportional to stretch. Infinite kinetics theory and experiments find a square root relationship[6] between regression and stretch at high stretch rates, but kinetics become important at low stretch rates and the dependence on flame stretch becomes stronger.

The figure coordinates assume the values of stretch are equivalent, whether derived from forced stretch[6] or from buoyant stretch[7]. The excellent correlation of the regression-rate data over the two-order-of-magnitude variation of stretch shows the reasonableness of this assumption.

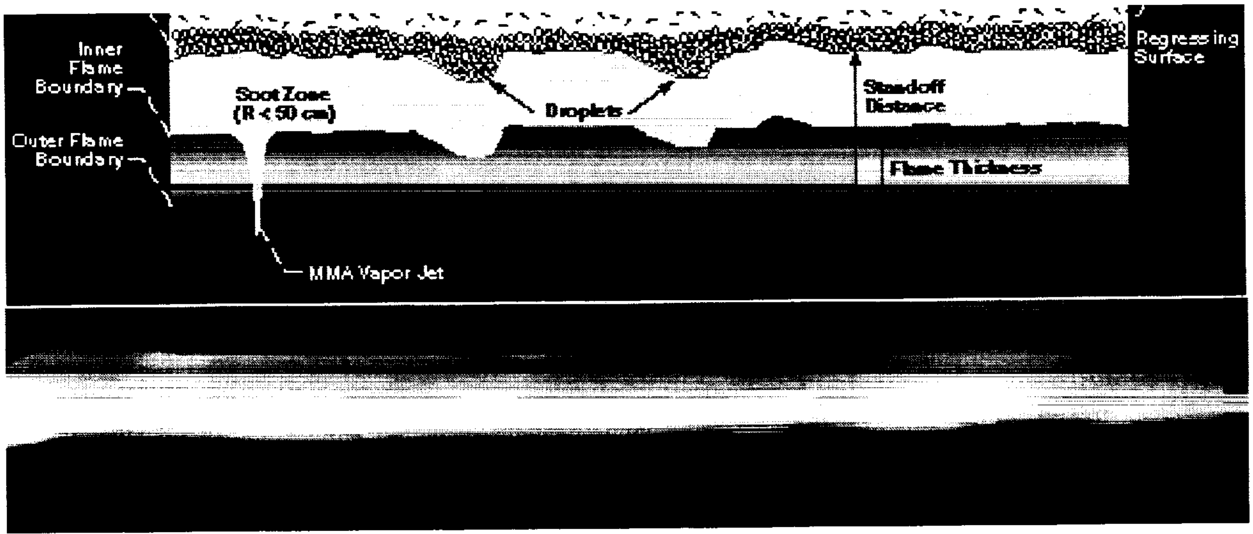

Figure 4: schematic of low stretch flame(top) along with actual flame photograph (bottom) for a stretch rate of $6\ s^{-1}$.

Buoyant low-stretch flames compare well with low-gravity low-stretch flames. A buoyant low stretch flame is shown in Fig.4. Through normal and microgravity testing we have found 1) flame standoff distances increase at low stretch, 2) reaction zones thicken at low stretch, 3) cooler flame temperatures at low stretch, 4) decreased heat flux back to the surface at low stretch, 5) decreased burning rates of fuel at low stretch, 6) increased relative heat loss at low stretch, and 7) quenching extinction is noted at low stretch rates of $1.5\text{-}2\ s^{-1}$.

Equivalent Low Stretch Apparatus Under Development

A concept of the apparatus is shown schematically in Figure 5. The concept uses the low stretch geometry [1] to simulate the conditions of the extraterrestrial environment through proper scaling of the sample dimensions to reduce the buoyant stretch in normal gravity. If successfully tested, the apparatus will be integrated into NASA's White Sands Test Facility's Atmosphere-Controlled Cone Calorimeter for evaluation as a new materials screening test method.

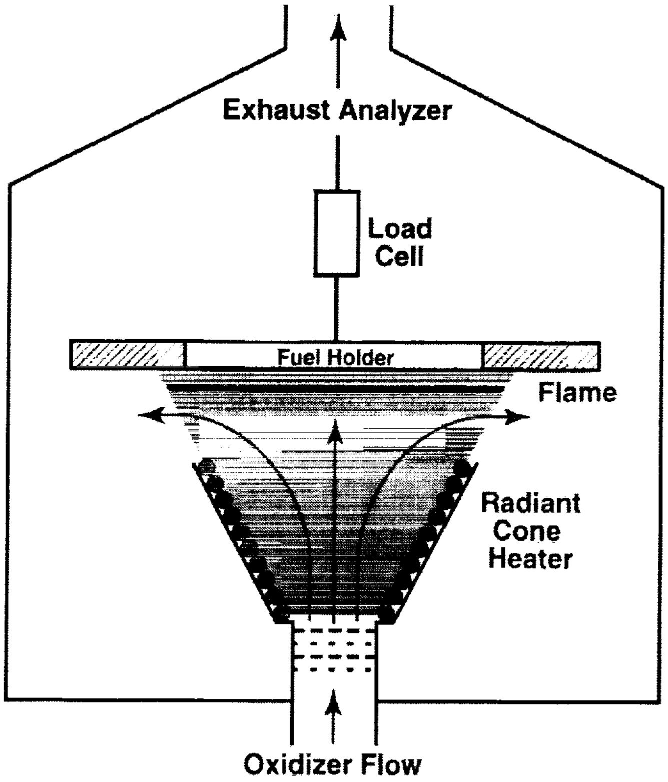

Figure 5: Equivalent Low Stretch Apparatus

The apparatus uses controlled forced-air flow to augment the low stretch to levels which simulate Lunar or Martian gravity levels. In addition, the effect of imposed radiant heat flux on material flammability can be studied with the cone heater.

Primary variables include material tested, imposed forced stretch rate (effective gravity level), radiant flux level, and oxygen concentration.

Data from the Apparatus will include ignition delay time, mass loss rate, heat release rate (O2 consumption), and product generation rates (CO, CO2, soot, THC).

Ignition limits and material flammability limits will be measured for selected ideal/practical materials. If extinction limits are determined in Earth-based low stretch experiments as a function of the percent of heat flux conducted into the solid, we can identify critical percent heat flux values for spacecraft. It would then be possible to design safe-use configurations in space to ensure non-flammability (ie sufficiently thick materials or sufficiently conductive substrates).

In addition to the development of the apparatus, a predictive model will be developed to predict flammability limits for a given material, using specific material properties, desired atmospheric composition, and extraterrestrial gravity environments as inputs to the prediction. The experimental and predicted results will be compared to evaluate the test method and predictive capability.

References

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