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Simplified model for predicting difference between flammability limits of a thin material in normal gravity and microgravity environments

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Abstract

Most flammability tests for a material to be used for manned spacecraft are conducted on the ground, although several studies have reported that the flammability limit in microgravity is different from that in normal gravity. Hence, an important task is to predict the margin between the limiting oxygen concentrations (LOCs) in normal gravity and microgravity. We set up a simplified scale model to describe the opposed-flow flame spread over a thin material and derived expressions for the Damköhler number (Da) and the nondimensional radiative loss factor (R_{rad}) for the flame spread over a thermally thin poly methyl methacrylate (PMMA) sheet. The empirical constants for these nondimensional numbers were evaluated by fitting with the experimental results in a N_2 balance. The obtained model was validated under varying gas-phase properties. First, we obtained the experimental blow-off limits via downward spread tests in normal gravity with different balance gases (N_2, Ar, and CO_2). We compared the predicted blow-off limits, which corresponded to the limiting oxygen index (LOI) condition, with the experimental results for each balance condition and found that the predicted limits agreed well quantitatively with the experimental results. Then, using Da and R_{rad}, we drew a flammability map for opposed-flow flame spread over a thin PMMA sheet, which predicted the flammable conditions under the LOI. The developed simplified model predicted the minimum LOCs (MLOCs) and the critical opposed-flow velocity for the N_2, Ar, and CO_2 balance conditions. The model underestimated the MLOCs because it considered the effect of either the radiation or the kinetics, whereas both these effects are actually coupled near the MLOC. Nevertheless, the predicted margin between the MLOC and the LOI illustrated the behavior of the flame spread near extinction.

Keywords: Flame spread; Extinction; Scale analysis; Microgravity

1. Introduction

Recently, human activity in space has increased and the duration of stay in spacecraft

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Nomenclature

A	pre-exponential factor
a_{abs}	absorption coefficient of gas
B_1	empirical constant for Da
B_2	empirical constant for R_{rad}
c_{BC}	empirical constant for buoyant flow velocity
c_{g}	specific heat of gas
c_{s}	specific heat of solid
Da	damköhler number
E	activation energy
L_{gx}	gas-phase diffusion length scale in x-direction
L_{gy}	gas-phase diffusion length scale in y-direction
L_{sx}	length of preheated solid phase
L_{sy}	thickness of preheated layer
R_{rad}	radiation loss factor
T_{f}	adiabatic flame temperature
T_{v}	vaporization temperature
T_{∞}	ambient temperature
V_{g}	opposed-flow velocity
V_{f}	flame spread rate
$V_{\mathrm{f,th}}$	flame spread rate in thermal regime
V_{r}	velocity relative to flame, $V_{\mathrm{r}} = V_{\mathrm{g}} + V_{\mathrm{f}}$
V_{cr}	critical opposed-flow velocity
W	width of fuel in z-direction
α_{g}	thermal diffusivity of gas, evaluated at T_{v}
ε	surface emissivity
λ_{g}	gas-phase conductivity evaluated at T_{v}
λ_{s}	solid-phase conductivity
η	nondimensional spread rate
ρ_{g}	gas density evaluated at T_{v}
ρ_{s}	solid density
τ	fuel half-thickness

such as the International Space Station (ISS) is becoming increasingly longer. Then, the reduction of fire risk in a microgravity environment and performing convenient flammability tests for materials used in space have become important research issues. Extensive studies have been conducted on flame spread over a thermally thin material with opposed flow under microgravity conditions [1–10]. One of the most characteristic features of a microgravity environment is the absence of buoyant flow, which is essential in normal gravity. Therefore, most of these previous studies were focused on flame behavior with a mild or slow flow whose velocity was smaller than that of the buoyant flow. Many studies conducted in the Space Shuttle and drop towers reported that flame spread with a slow ambient flow was suppressed by radiative heat loss, which eventually caused radiative extinction under a quiescent condition [4-6]. Thus, flame spread in microgravity may be considered as being on the “safe side.”

Olson et al. [6] investigated the flame spread in microgravity under varying ambient flow velocity and reported that the spread rate achieved the maximum peak with an ambient flow velocity of 6 cm/s. Kumar et al. [7] also conducted numerical simulations and demonstrated that the minimum oxygen concentration required for a thin material to burn became lowest when the flow velocity was about 5 cm/s. Similar results have been reported by other researchers, and it is common knowledge that the curve of the limiting oxygen concentration (LOC) versus the opposed-flow velocity is U-shaped [8]. This trend implies that the flammability limit of a thin material is lower in microgravity than in normal gravity. Despite this fact, however, many flammability tests have been conducted in normal gravity, such as NASA STD-6001 or ASTM D2863. The obtained results are extremely vast, but using the collected data to estimate the flammability in microgravity requires careful consideration, because the minimum oxygen concentration in microgravity may be much lower than that in normal gravity. Olson et al. [9] reported that the upward LOI (ULOI) and the maximum oxygen concentration (MOC) varied depending on the gravity level and the kind of material used. Consequently, in order to confirm the fire safety at different gravity levels, including microgravity, additional flammability tests should be conducted under the corresponding gravity conditions or detailed numerical simulations should be performed; however, both these approaches are time consuming and expensive. Hence, the objective of the present study was to develop a simple model that can predict the difference between the flammability limits of thin materials in normal gravity and microgravity environments. To this end, we defined the minimum limiting oxygen concentration (MLOC) as the oxygen concentration at which the flame cannot exist with any opposed-flow velocity. We also defined the critical opposed velocity V_{cr} at which the MLOC is observed. We derived two nondimensional variables, including an experimental constant, and predicted the MLOC and V_{cr} in microgravity as well as the LOI in normal gravity. In order to validate the developed model, we first investigated the effect of diluent-gas properties on the flammability map; to this end, we conducted flame spread