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The critical flow velocity for radiative extinction in opposed-flow flame spread in a microgravity environment: A comparison of experimental, computational, and theoretical results

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ABSTRACT

The effect of opposing flow on flame spread rate over thin solid fuel is investigated with the help of scaling theory, a comprehensive computational model, and experiments conducted aboard the International Space Station. While spread rate over thin fuels is independent of the opposing flow velocity in the thermal regime, in the microgravity regime, where the opposing flow can be very mild or even completely absent in the absence of buoyancy induced flow, the spread rate is known to decrease as the opposed flow is reduced. Under certain conditions, this can lead to flame extinguishment at a low enough flow velocity. This paper combines scaling arguments with computational results to predict a critical flow velocity for such flame extinction. Results from the recently conducted limited number of space based tests, presented in this paper, seem to confirm the prediction validating the closed-form formula for the critical extinction velocity.

1. Introduction

Opposed-flow flame spread over thermally thin fuels is one the most fundamental topics in the study of fire spread. The physics of flame spread is considerably simplified in this configuration because the flame spreads steadily and the fuel can be assumed to be uniformly heated across its thickness. Moreover, in the thermal regime, gas-phase and pyrolysis chemistry can be considered infinitely fast compared to the residence time $t_{\text{res}} \approx L_g/V_g \approx \alpha_g/V_g^2$, the time spent by the oxidizer as it passes through the length $L_g \approx \alpha_g/V_g$ of the flame leading edge, producing a simplified closed-form expression for the thermal limit [1,2] of the flame spread rate. The spread rate is independent of flow velocity V_g, inversely proportional to the fuel thickness, and directly proportional to a non-dimensional coefficient known as the de Ris coefficient $F = (T_f - T_v)/(T_v - T_\infty)$, where T_f is the adiabatic flame temperature, T_v is the fuel vaporization temperature, and T_∞ is the ambient and virgin fuel temperature. As the opposed flow velocity is increased, the residence time being inversely proportional to the square of velocity, finite-rate kinetics in the gas phase becomes important leading ultimately to the blow-off extinction. This kinetic regime has been experimentally [3] and computationally [4] studied and the spread rate, normalized by its thermal limit, has been correlated to the non-dimensional Damkohler number, the ratio of the chemical and residence time. The downward spread in a quiescent 1-g environment can be considered a special case of opposed-flow flame spread with buoyancy induced flow providing the opposing flow velocity [5].

In a microgravity environment, the opposing flow can be very mild and even completely absent in the perfectly quiescent situation of zero gravity. Numerical [6,7] and experimental [8,9] studies have established the radiative regime in the mild opposed-flow environment in which the flame spread rate decreases as the opposed-flow velocity is reduced leading to flame extinguishment [10] if the flow velocity is sufficiently low. This result is also dependent on other ambient conditions as steady spread over thin fuels in a perfectly quiescent environment has been established at higher oxygen levels [11]. The critical velocity, defined as the opposed-flow velocity below which steady spread rate is not observed in a microgravity environment, has been shown to depend on oxygen level, but its dependence on other parameters such as fuel thickness are still not well known. There is no closed-form formula, verified by experimental results that can be used to predict the critical velocity.

In this work, recent experimental work for flame spread over thin sheets of PMMA performed in the International Space Station is reported. The experimental results are analyzed to determine the critical velocity for different fuel thicknesses and ambient oxygen levels. The results are compared with predictions from a simplified analysis and computational results from a two-dimensional steady-state

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Nomenclature

c	specific heat at constant pressure, kJ/kg·K
F	de Ris flame coefficient
L	length scale, m
T_∞	ambient temperature, K
T_v	fuel vaporization temperature, K
T_f	adiabatic flame temperature, K
t	time, s
V_g	velocity of the oxidizer, m/s
V_f	absolute spread rate, m/s
W	width, m

Greek symbols

α_g	thermal diffusivity of gas, evaluated at T_v, m^2/s
ε	surface emissivity
λ_g	gas-phase conductivity evaluated at T_v, kW/m·K
η_f	non-dimensional spread rate
η_g	non-dimensional flow velocity
ρ_g	gas density evaluated at T_v, kg/m^3
ρ_s	solid density, kg/m^3
τ	fuel half-thickness, m
σ	Stefan–Boltzman constant, $kW/(m^2 \cdot K^4)$
$\Re_0$	non-dimensional radiation number

Subscripts

cr	critical
g	gas phase
res	residence
s	solid phase
x, y	coordinates

flame spread model. A predictive formula for the critical velocity is proposed in this work.

2. Experimental setup

The Burning and Suppression of Solids-II (BASS-II) apparatus [12] in the International Space Station is depicted in Fig. 1. It is a combustion tunnel, a 76 mm square duct, where the PMMA fuel samples, 20 mm wide and about 95 mm long with the thickness ranging from 100 μm to 400 μm are burned in an opposed-flow configuration. A fan forces a flow of an oxygen–nitrogen mixture through flow straighteners from the right to the left and the sample is ignited at the left end. Depending on the flow velocity and oxygen concentration, a steady flame is established which spreads from the left end of the sample toward the right end. The oxygen level can be adjusted to 21% or below and the flow velocity can range from 0 to 50 cm/s. A hot wire anemometer is used to calibrate the flow velocity with fan voltage, which is used to determine the flow velocity.

Experiments were conducted in the Microgravity Science Glovebox of ISS by two crew members. Operation instructions were communicated from NASA Glen Op Center in real time as the experiment progressed. Each test starts by creating a desired opposing flow by adjusting the fan voltage. After the flow stabilizes, the igniter is turned on until a visible flame is observed. The igniter is then turned off and the flame is photographed with a high resolution digital still camera with a frame rate of 1 per second. A radiometer is used to confirm flame extinction when the visible flame goes out. In some of the tests, the flow velocity is changed during the spread to maximize the test matrix without having to burn additional samples.

3. Data analysis

A Matlab based image processing application has been developed at SDSU to obtain flame spread rate and other information from the sequence of top-view digital photographs. A typical color image of the top view 10 s after ignition is shown in Fig. 2(a) for flame spread over 100 μm thick PMMA sheet for the ambient conditions of 20.7% oxygen, 1 atm and an opposed-flow velocity of 2.5 cm/s. The dots along the axis, 6 mm apart, are superimposed on the image to help display the spatial resolution of the image. The ignition wire, glowing red at $x = 36$ mm, and the burnout location, the black line at $x = 42$ mm are visible in this picture. To eliminate the effect of edge propagation, the central part of the flame, bracketed between the two white lines parallel to the axis and about 14 mm apart, is isolated. The RGB values of each pixel of the central slice are then converted to an intensity value using built-in Matlab tools. Across the width of the section, these intensity values are averaged, producing a two-dimensional representation of the flame as shown in Fig. 2(b). The variation of the width-averaged intensity along the x direction (axis) is shown in Fig. 2(c). The leading edge of the flame is determined by locating a fixed threshold intensity. A value of 30 for the threshold value was

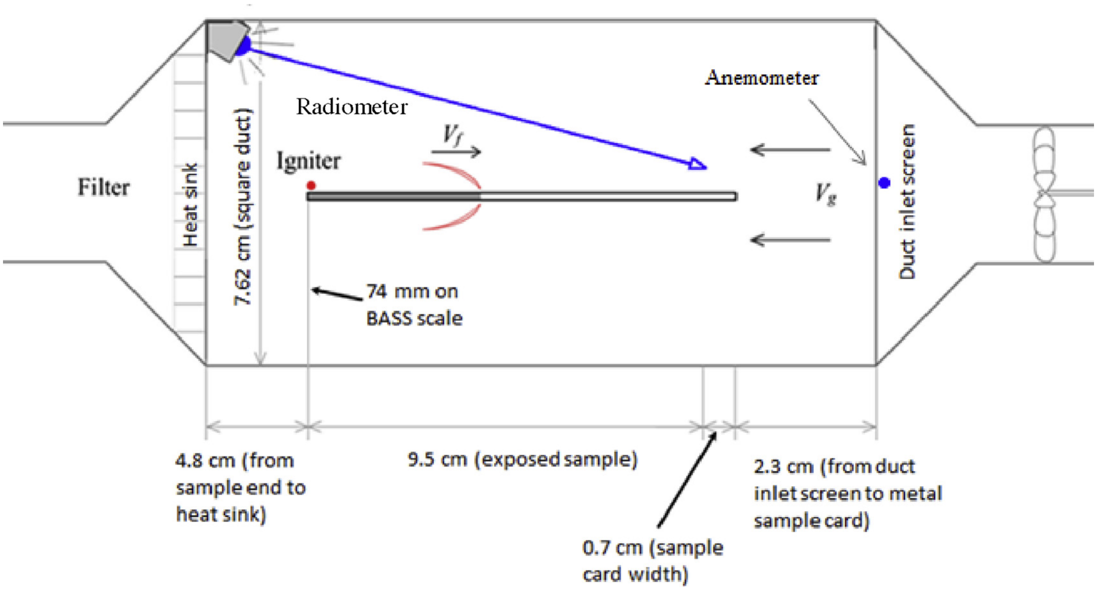

Fig. 1. Schematic of the BASS-II combustion tunnel.

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