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Opposed-flow flame spread: A comparison of microgravity and normal gravity experiments to establish the thermal regime



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ABSTRACT

The thermal regime of flame spread over solid fuels constitutes the reference condition for all other flame spread research. Although the theory of flame spread in the thermal regime is well understood, the well-known closed-form formulas for flame spread do not compare well with available experimental data. The comparison is further complicated by the fact that establishing a thermal regime in a normal-gravity environment is difficult because of the buoyancy induced flow which may usher in finite-rate kinetics effect. As a result, even the transition thickness, when a fuel can be considered a thermally thick fuel, still lacks a widely accepted formula.

In this work we present opposed-flow flame spread data over varying thicknesses of poly-methyl methacrylate (PMMA) obtained in the International Space Station where the opposing flow velocity can be reduced arbitrarily without any interference from the gravity induced flow. We also present a larger set of spread rate data for the downward spreading configuration at normal gravity. A comparison between the two data set allows us to establish the thermal limit for thin fuel for which the spread rate is independent of the opposing flow velocity. The classical thin-fuel spread rate formula is shown to fit well with the experimental results provided the adiabatic flame temperature is used in the flame coefficient that appears in the formula. The experimentally determined flame coefficient along with downward flame spread data for thick fuels are used to develop a closed-form expression for the transition thickness between thermally thin and thick fuels for downward spread in the thermal regime.

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1. Introduction

Opposed flow flame spread over solid fuels has been under investigation for about four decades [1–3]. Researchers have long desired to understand and predict the behavior of fire in different situations and under different conditions. While flame spread in the upward configuration is closely related to fire safety studies, it is also quite complex to model because the flame spread process is not steady and the flame size quickly becomes very large. In the downward configuration, where a flame spreads down a solid fuel sample vertically downward, the flame behaves in a two-dimensional, quasi-steady (while the flame spread rate is constant, the flame shape may evolve in an unsteady manner), quasi-laminar (the flame trailing edge may show fluctuating pattern) manner with the steady flame spread rate being a function of fuel and environmental conditions. Because experiments on downward spread can be inexpensive to perform [4], theories to describe the

mechanism of flame spread in a quantitative manner can be tested and refined. Findings from this simplified configuration can be useful for more practical configurations, such as upward or horizontal spread, given the commonality of various physics that participate in the mechanism of flame spread [5].

Even in this simplified configurations a number of complexities can arise. Based on the thickness of the fuel sample, it may or may not be uniformly heated across its thickness. The pyrolysis chemistry to predict the burning rate of the fuel may not be well known [6]. The gas phase chemistry used in computational models mostly assumes an overall single-step reaction. If the buoyancy generated flow is strong enough or the oxygen level is low enough (or both), a competition between the combustion time and residence time may usher in chemical kinetics effect [7] on the flame, leading to a reduction of spread rate or even extinction. Yet another complication can arise if the opposing flow velocity is too low, as in the case of a microgravity environment. A higher residence time makes both surface and gas radiative effects increasingly important [8]. Obviously, despite the simplification that the assumption of a two-dimensional laminar flow brings in, a

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Nomenclature

c_g	specific heat of gas, kJ/kg K
c_s	specific heat of solid, kJ/kg K
F	flame constant, Eq. (4)
L_g	gas-phase diffusion length scale, m
T_∞	ambient temperature, K
V_g	velocity of the oxidizer, m/s
V_f	absolute spread rate, m/s
V_r	velocity relative to the flame, $V_r = V_g + V_f$

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

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, $kW/(m^2 \cdot K^4)$

Subscripts

adb	adiabatic
chem	chemical
eff	effective
g	gas phase
rad	radiation
res	residence
s	solid phase
th	thermal
vap	vaporization

theory that includes gas phase radiation, chemical kinetics in the gas phase, and pyrolysis kinetics is still too complicated to yield a solution without the application of numerical analysis. This is why de Ris [9] introduced the *thermal regime*, where the theory is drastically simplified by assuming that the opposing flow velocity is not too small or not too large so that neither radiation nor chemistry plays any significant role in the mechanism of flame spread. As a result an analytical solution of the governing equations is possible with the neglect of radiation and assumption of infinite-rate kinetics; the closed-form spread rate formulas by de Ris and Delichatsios [9,10] in the thermal regime provide a baseline for non-dimensionalizing experimental data and understanding the parametric dependence of flame spread with fuel and environmental conditions.

These well known formulas for opposed-flow spread rate, however, have some drawbacks. The flame temperature used in the formula is based on a linearized mass diffusion theory and can be quite different than the thermodynamic adiabatic flame temperature. Also, use of constant properties in the theory allows room for significant variability in how properties such as thermal conductivity of air, specific heat, etc. are evaluated. As a result, when an experimental spread rate does not agree reasonably well with the theoretical prediction, it is not clear whether the disagreement is due to incorrect use of properties in the formula or due to more fundamental reason such as the flame spread is not in the thermal regime.

The opposed-flow flame spread experiments, where the opposing flow velocity can be directly controlled in a flow tunnel [11,12] can easily create a high flow velocity where gas phase chemistry becomes important due to shortened residence time. However, the opposed flow cannot be arbitrarily reduced. Even in a quiescent environment, there is no guarantee that the buoyancy created flow is weak enough to justify an assumption of infinite-rate kinetics.

In this work we use the gravity-free environment of the International Space Station to continue the opposed-flow flame spread experiment to its logical conclusion by reducing the opposing flow velocity to any desired value without any interference from buoyancy in search of the elusive thermal regime. We present data from both downward experiments and microgravity experiments for the same fuel under the same environmental conditions (except for gravity level of course) for the first time. A simplified scale analysis is carried out to establish the elusive thermal regime experimentally. The results also help us determine

the transition thickness between thermally thin and thermally thick fuels for downward flame spread.

2. Scale analysis

Flame spread is determined by the competing physics at the flame leading edge. To establish the thermal regime through a scale analysis, a comprehensive sketch of all the major participants is presented in Fig. 1, where different types of heat transfers are shown in bold arrows, length scales at the leading edge, and competing time scales with the subscripts g indicating gas phase and s indicating the solid phase. The heat transfer to the virgin fuel, the driving mechanism of any flame spread [5], involves conduction through the gas (*gy,cond*), conduction through the solid (*sx,cond*), surface radiation (*s,rad*), and gas radiation feedback (*g,rad*). Of these, forward conduction through the solid has been shown to be relatively unimportant theoretically [9] and experimentally [13]. It should be mentioned that high lateral (perpendicular to spread rate) thermal conductivity, which can be different from the forward conductivity in composite materials, has been experimentally [14] shown to influence the spread process strongly. In this analysis, however, the focus will be on homogeneous fuel such as PMMA ($C_2H_8O_2$). The radiative effects is also neglected (the rationale to be discussed later), leaving gas to solid conduction as the dominant heat transfer mode.

By comparing the forward heat conduction to the advection term at the flame leading edge, the diffusion length scale can be established as $L_g \approx \alpha_g/V_g$, where α_g is the thermal diffusivity and V_g is the opposing flow velocity. Therefore, the gas residence time, time spent by the oxidizer at the leading edge, is given as $t_{g,res} \approx L_g/V_g \approx \alpha_g/V_g^2$. Assuming gas phase conduction is the primary heating mechanism of the preheat zone, L_g must also be the solid phase heating length. The fuel residence time, time spent by the fuel at the leading edge, is then given by $t_{s,res} \approx L_g/V_f \approx \alpha_g/(V_g V_f)$, where V_f is the flame spread rate, the desired unknown.

The first assumption of the thermal regime is that $V_f \ll V_g$ so that $t_{s,res} \gg t_{g,res}$. The combustion time scale in the gas phase, $t_{g,chem}$, can be defined as the time necessary for the combustion reaction to be complete at the flame leading edge raising the gas temperature to $T_{f,adb}$, the adiabatic flame temperature. Similarly, the chemical time scale in the solid phase for the pyrolysis of fuel, $t_{s,chem}$, can be defined as the time necessary for the fuel

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