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Influence of gap height and flow field on global stoichiometry and heat losses during opposed flow flame spread over thin fuels in simulated microgravity

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ABSTRACT

This study characterizes thin fuel opposed flow flame spread in simulated microgravity for a range of gap heights and airflow velocities in a Narrow Channel Apparatus (NCA). One objective was to estimate gap heights that suppress buoyancy without promoting excessive heat losses to the channel walls. A corollary of this objective was to assess the dependence of heat losses on the channel height. A second objective was to determine the influence of global combustion stoichiometry on simulated microgravity flame spread in the NCA. Whatman 44 filter paper was used for NCA gap heights ranging from 6–20 mm (half-gap below and above sample) and average opposed flow velocities 1–40 cm/s. Flames at low flows were fuel rich when the forced flows were of the same magnitude as the diffusive flow. For thin fuels, a full gap of 10 mm (5 mm half-gap) provided a compromise between buoyancy suppression and heat loss. Calculations were made of flame stoichiometry and of the influence of the velocity profile on flame spread rates (comparing it with previous theory). This part of the analysis provided support for the velocity gradient theory of flame spread. The information provided in this work on the theoretical nature of opposed flow flame spread over thin fuels is based on experimental measurements in simulated microgravity conditions.

1. Introduction

Studies of flame spread over thin and thick fuels [1–5] demonstrate that the induced buoyant flow can be reduced by spatially confining the flow vertically. A facility for accomplishing this goal called the Narrow Channel Apparatus (NCA), shown schematically in Fig. 1, has been under development for simulated microgravity flame spread research [1,2,4]. For thermally thin fuels, the flame spread rate in the NCA is compared with NASA's Zero-gravity research facility by varying the total pressure, oxidizer velocity and oxygen concentration [1]. Flames in the NCA look similar to those studied in microgravity and exhibit similar spread rates to microgravity flames for thin fuels where direct comparisons are possible [2]. The flame spread rate has also been measured and compared in normal and microgravity at different pressures in the cylindrical tube geometry [3]. Both concurrent and opposed flow flame spread in the NCA have been studied for thermally thick solid fuels [4,5]. Different channel configurations have been studied to analyze flame front propagation using analytical, numerical and experimental techniques for thin solid fuels [6]. Phenomena such as flame fingering and a low flow quenching limit have been demonstrated in the NCA that are characteristic of actual opposed flow microgravity flame experiments [2]. These phenomena have never been observed in NASA Test 1 [3], which is described in Ref. [7].

The research group of Matsuoka has examined opposed flow flame spread in narrow channels. In [8] flame spread in a narrow channel whose inner surfaces consisted of two oppositely facing thermally thick PMMA plates was examined. For gap spacings of 1-2 mm fingering patterns were observed. In addition, a plot of the opposed flow velocity versus the proxy $1/h$ for heat loss produced a flammability map similar to Fig. 21 of [2], indicating that this configuration produced a flame response ranging from steady spread to flamelet oscillation and fingering to extinction. The authors also examined single PMMA sheets (the opposite wall being inert) and used the data to examine their theoretical correlation based on change of flame behavior as a function of the modified Lewis number $Le_{eff} = \alpha_{eff}/D$ having effective thermal diffusivity

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Nomenclature

$c_{p,f}$	Fuel specific heat
$c_{p,g}$	Gas specific heat
c_s	Specific heat of solid [8]
c_f, c_g and c_q	Proportionality constants
D_{o2}	Oxygen diffusivity
$(\frac{F}{A})_{mass,\ stoich}$	Stoichiometric fuel to air mass ratio
h	Narrow channel gap height
h_c	Heat transfer coefficient
k	Thermal conductivity of gas at temperature $\bar{T}$
k_f	Fuel thermal conductivity
k_g	Gas thermal conductivity
l_f	Length of the heat source
Le	Lewis number
Le_{eff}	Effective Lewis number [8]
$\dot{m}_f$	Mass feed rate of fuel
$\dot{m}_g$	Mass feed rate of gas
$\dot{m}_{ox}$	Consumed mass feed rate of oxygen
$\overline{Nu}_{l_f}$	Nusselt number based on length l_f
Pe_h	Peclet number for channel flow
$\dot{Q}_{conv}$	Convection heat loss rate
$\dot{Q}_{flame}$	Total flame heat release rate
$\dot{Q}_f$	Solid fuel enthalpy rise rate
$\dot{Q}_g$	Gas enthalpy rise rate
$\dot{Q}_{in}$	Heat input rate into the control volume
$\dot{Q}_{out}$	Heat release rate out of the control volume
$\dot{Q}_P$	Product gas enthalpy rise rate
$\dot{Q}_{rad}$	Radiative heat loss rate
$\dot{Q}_{loss}$	Total heat loss
$\hat{Q}_{loss}$	Dimensionless heat loss
Re_{l_f}	Reynolds number based on length l_f
t_f	Fuel thickness
T_F	Flame temperature
T_{in}	Inlet temperature
T_{out}	Outlet temperature
T_s	Surface temperature
T_v	Vaporization temperature
T_∞	Surrounding temperature
$\bar{T}$	Heated segment temperature
$u(y)$	Parabolic velocity distribution
U_g	Unburned gas velocity
V_f	Flame velocity
$\bar{V}_g$	Average gas flow velocity
$V_{g,\ diff}$	Diffusion velocity for oxygen
$\hat{V}_g$	Dimensionless opposed flow velocity
V_r	Relative velocity
w	Fuel width
Y_{ox}	Mass fraction for oxygen

Greek

α_{eff}	Effective thermal diffusivity [8]
α_f	Fuel thermal diffusivity
α_g	Gas thermal diffusivity
δ	Thermal thickness [8]
δ_o	Stoichiometric oxygen distance
$\hat{\delta}_o$	Dimensionless stoichiometric oxygen distance
δ_g	Gas preheat length scale
δ_s	Solid preheat length scale
δ_q	Quenching distance
δ_w	Characteristic dimension along the width of the sample
ϵ	Emissivity for cellulose
ϕ	Overall equivalence ratio
λ_g	Gas conductivity [8]
λ_f	Solid conductivity [8]
ν	Viscosity of gas at temperature $\bar{T}$
ρ_f	Fuel density
ρ_g	Gas density
σ	Stefan–Boltzman constant

given by

$$\alpha_{eff} = \frac{\lambda_g(h-\delta)+\lambda_s\delta}{\rho_g c_{pg}(h-\delta)+\rho_s c_s\delta}.$$

Here subscripts g and s denote solid and gas, λ is the thermal conductivity, ρ is the density and c is the heat capacity. Also, h is the gap width and δ is the thermal thickness. Clearly $\delta = 0$ produces the pure gas α_{eff} whereas $\delta = h$ produces the solid α_{eff}. Corrugated and otherwise distorted flame behavior was found to correlate with Le_{eff} calculated using α_{eff}.

In light of the previous work and discussion, there are three major goals of the present study, which addresses only thermally thin fuel samples. One goal is to determine the influence of global combustion stoichiometry on simulated opposed flow microgravity flame spread. This fundamental quantity—its global stoichiometry—characterizes the spread process and clarifies changes that occur in the flame behavior, even though it is well known that the local opposed flow flame spread process is stoichiometric. The first goal of this article is to quantify the various experimentally measured behaviors analytically through correlations and scaling parameters derived from an order-of-magnitude, predominantly control volume analysis.

A second goal is to evaluate the role of gap height in the NCA. The evidence of a trade-off between buoyant suppression and flame quenching through heat losses is of interest for the further development and refinement of a standard test method for spacecraft applications. The gap height will influence flame spread rates, the flame combustion rate, and heat losses to the NCA walls. Since the purpose for diminishing the gap height is to suppress buoyancy so that microgravity conditions might better be simulated, there must be a compromise between decreasing the gap height to suppress buoyancy while simultaneously increasing the heat losses from the flame to values not found in pure microgravity flame spread.

A third goal is to quantify the accuracy of flame spread models, e.g. [9]. Because of the nature of the Hagen–Poiseuille flow field in the NCA, the influences of the flow field can be systematically examined, enabling direct comparisons to be made between the Oseen and velocity gradient models.

The article is organized as follows. A description of the facility and the experimental results is provided in Sections 2 and 3. Section 4 produces theoretical correlations for the global flame stoichiometry problem. Section 5 produces a theoretical analysis that leads to correlations that characterize the various length scales of the problem and their relation to flame spread in an opposed flow. These correlations are evaluated using the experimental measurements. Section 6 examines the control volume analysis for heat losses from the flame by radiation, convection and enthalpy change of the gases. Section 7 provides a discussion and conclusions.

2. Experiment description

The goal of the NCA is to reduce buoyant convection by constricting the channel height, h without producing excessive heat losses to the NCA surfaces. When operating as intended, the reduction of h causes the vertical, locally cellular flow produced by