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Upward flame spread in large enclosures: Flame growth and pressure rise

Sandra L. Olson [a,*], Suleyman A. Gokoglu [a], David L. Urban [a], Gary A. Ruff [a], Paul V. Ferkul [b]

[a] NASA Glenn Research Center, Cleveland, OH, United States
[b] National Center for Space Exploration Research, Cleveland, OH, United States

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Abstract

Upward flame spread tests were conducted on thin fuels in a sealed chamber capable of accommodating large-scale samples (1 m length). The primary objective of these tests was to measure flame spread and pressure rise in a large sealed chamber during and after flame spread and to characterize that data as a function of sample material, initial pressure, and sample size. The flame spread rate as a function of initial pressure has been measured for a given fuel and found to vary as $\sim P^2$ in agreement with Grashof number scaling. The burning rate per unit area for a fixed pressure has been shown to be a constant independent of fuel area density or quantity of fuel burned. A steady upward flame spread was observed only at low pressure. The pressure rise in a sealed chamber has been shown to scale with the quantity of fuel burned, and the peak pressure has been shown to scale inversely with initial pressure, in agreement with the pressure dependence of the characteristic time associated with a simple analytical solution of an energy balance. The pressure rise per mass of fuel burned exhibits an exponential decay with burn-time, also in agreement with the analytical solution.
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Keywords: Upward flame spread; Fabric; Pressure rise

1. Introduction

Many material tests have been conducted to characterize combustion and flammability characteristics of materials [1], but experiments are typically done with relatively small samples ($\lesssim$ 0.1 m scale). A major safety concern for any sealed vehicle is the environmental effect of a large-scale burn. Large scale fire events have occurred in sealed passenger vehicles, such as aircraft and spacecraft.

Large-scale upward flame spread in normal gravity is difficult to study due to the rapid flame spread and large scale of the apparatus required for the testing. Notable studies of thin-fuel upward flame spread include Markstein and de Ris [2] who provided quantitative experimental measurements and comparison with modeling, Quintiere et al. [3] who also performed large-scale upward flame spread tests, Honda and Ronney [4]

* Corresponding author. Address: NASA Glenn Research Center, 21000 Brookpark Road, MS 77-5, Cleveland, OH, USA. Fax: +1 216 433 8050.

E-mail address: sandra.olson@nasa.gov (S.L. Olson).

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Nomenclature

A	chamber interior surface area for convective heat transfer, m^2
c_v	mass-based specific heat of gas at constant volume, J/kg-K
HRR	Heat-release rate due to combustion, W
h	heat transfer coefficient during flame spread, W/m^2-K
h'	heat transfer coefficient after flame extinguishment, W/m^2-K
P	pressure, kPa (psia)
Q	thermal energy accumulation, J
q	heat-release or loss rate, W
SIBAL	fuel custom 75% cotton- 25% fiberglass (by mass) fabric
T	temperature, K
t	time, s
V	total available gas volume of the sealed chamber or vehicle, m^3
VF-13	Vacuum Facility 13, at NASA Glenn Research Center

Greek characters

ρ	gas density, kg/m^3
τ	characteristic time for temperature decay, s

Subscripts

b	burn value
comb	due to combustion
cond(local)	due to local conduction
conv	due to convection
g	gas-phase value
o	initial value
peak	peak value
rad	due to radiation
w	wall value

who provided scaling guidelines for different flame spread regimes, and Feier et al. [5] and Kleinhenz et al. [6] who looked at partial-gravity upward flame spread at different pressures to compare with Grashof number scaling. However, none of these studies has reported on the pressure rise associated with the large scale fire, which could cause catastrophic rupture of the vehicle, such as what occurred in Apollo 1.

The objective of this paper is to describe and analyze normal-gravity upward flame spread results and measured pressure rise in a large sealed chamber as a function of sample material, quantity of material burned, and initial pressure.

2. Experimental apparatus

A large-volume sealed chamber was used for upward flame spread tests to simulate the effect of a large fire on the pressure rise inside a spacecraft. The chamber had an inner diameter of 1.5 m and a height of 3.6 m, yielding a total volume of 6.35 m^3. For comparison, the Soyuz capsule has a pressurized volume of 10 m^3, and a fraction of that volume is taken up by equipment and three crewmembers.

An experimental rack was fabricated to fit into the chamber. It consists of an aluminum frame with transparent Lexan walls to hold the sample card while allowing video imaging of the test. In the center of the frame, a 1.6×10^{-3} m-thick anodized black aluminum sample card is mounted, as shown in Fig. 1. Two types of sample cards were used: a four-sample card (each sample was 0.125 m wide by 1 m long) version as is shown in Fig. 1, and a single sample card (with a single large sample 0.5 m wide by 1 m long). Each card had igniter wires at the bottom of the long samples, to provide upward spreading flames. White lines every 0.1 m were marked on the sample cards to provide a permanent scale in the video images. The igniter wires were Kanthal A-1 29 gauge resis-

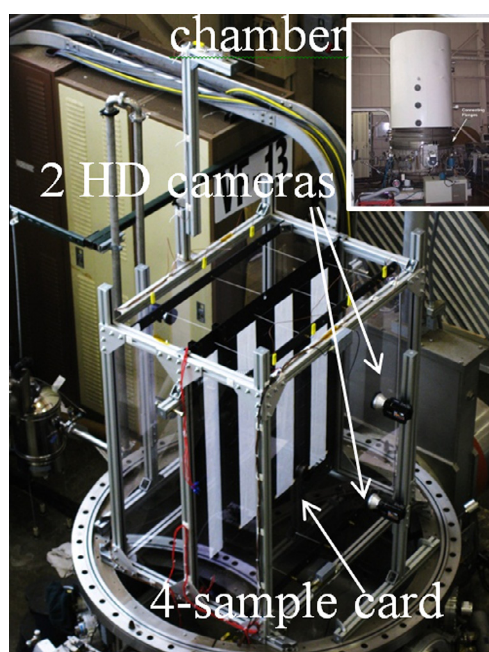

Fig. 1. Experiment rack schematic inside the VF-13 facility (shown in inset).