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Limiting conditions for flame spread in fire resistant fabrics

Andres F. Osorio [a,*], Carlos Fernandez-Pello [a], David L. Urban [b], Gary A. Ruff [b]

[a] Department of Mechanical Engineering, University of California, Berkeley, CA 94720, USA
[b] NASA John H. Glenn Research Center, Cleveland, OH 44135, USA

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Abstract

Fire resistant (FR) fabrics are used for astronauts, firefighter and racecar driver suits. However, their fire resistant characteristics depend on the environmental conditions and require study. Particularly important is the response of these fabrics to varied environments and radiant heat from a source such as an adjacent fire. In this work, experiments were conducted to study the effect of oxygen concentration, external radiant flux and oxidizer flow velocity on the concurrent flame spread over two FR fabrics: Nomex HT90-40 and a Nomex/Nylon/Cotton fabric blend. Results show that for a given fabric the minimum oxygen concentration for concurrent flame spread depends strongly on the magnitude of the external radiant flux. At increased oxygen concentrations the external radiant flux required for flame spread decreases. Oxidizer flow velocity influences the external radiant flux only when the convective heat flux from the flame has similar values to the external radiant flux. The results of this work provide further understanding of the flammability characteristics of fire resistant fabrics in environments similar to those of future spacecrafts.

Keywords: Fire-resistant; Flame spread; Limiting oxygen index; Charring

1. Introduction

Potential future space exploration missions by NASA or other international space agencies together with commercial space exploration spurred by lower operational costs have the potential to encourage the design of a new generation of spacecrafts and increase the number of humans traveling to space. An increased human presence in space also poses many challenges, particularly in human safety. Fire in a spacecraft environment represents a particularly dangerous situation given the combined effects of extended periods of time, confined space, low-pressure, elevated oxygen concentrations, low flow velocities and micro, or partial, gravity. Ignition and burning of fabrics and other combustible materials during a spacecraft mission could compromise mission success, but most importantly astronaut safety. The determination of the flammability characteristics of fabrics of both non-fire resistant (NFR) and fire resistant (FR) is important for fire safety purposes.

* Corresponding author. Address: Department of Mechanical Engineering, University of California, Berkeley Mailstop 1740, Berkeley, CA 94720, USA. Fax: +1 510 642 1850.
E-mail addresses: andres.osorio@berkeley.edu (A.F. Osorio), ferpello@me.berkeley.edu (C. Fernandez-Pello), david.urban@nasa.gov (D.L. Urban), gary.a.ruff@nasa.gov (G.A. Ruff),

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Nomenclature

ΔH_c	heat of combustion
$\Delta H_p(T,t)$	time and temperature dependent heat of pyrolysis
$\dot{m}''$	mass loss rate
$\dot{Q}'$	heat release rate per unit length
$\dot{q}''_{ext}$	external radiant flux
$\dot{q}''_{fr}$	radiant flux from the flame to the solid
$\dot{q}''_{MAX}$	maximum external radiant flux at sample leading edge
$\dot{q}''_{MIN}$	minimum heat flux for flame spared
$\dot{q}''_{sr}$	reradiation from the solid
ρ_g	gas phase density
ρ_s	solid density
c	generic constant
c_g	specific heat of the gas phase
c_s	specific heat of the solid
g	gravity
k_g	gas phase thermal conductivity
l_b	burn length
l_f	flame length
l_h	heated length
l_p	pyrolysis length
s	solid thickness
t	time
t_b	gasification time
T_f	flame temperature
T_o	solid initial temperature
T_p	pyrolysis temperature
U_∞	oxidizer flow velocity
V_f	flame spread rate

Abbreviations

LOI	limiting oxygen index
ULOI	upward limiting oxygen index
MOC	maximum oxygen concentration
FR	fire resistant
NFR	non-fire resistant

Several works conducted in normal and reduced gravity have characterized the ignition and flame spread characteristics of many thin materials under varying conditions of material thickness, external heat flux, oxygen concentration, pressure and forced flow velocity. Particularly relevant for the present work are the studies of [1–3] regarding the limiting oxygen concentrations, flammability and flame spread characteristics of FR fabrics. The limiting oxygen index (LOI) and maximum oxygen concentration (MOC) are two oxygen indices used to measure the flammability of a material. In its most common definition, the LOI is the lowest oxygen concentration that supports a flame [1,4]. In other applications, the LOI and MOC have been defined in terms of NASA's upward propagation test NASA-STD-6001 Test 1 [5]. Using this test, the LOI is defined as the oxygen concentration at which a material passes NASA-STD-6001 Test 1 approximately half the time. The MOC is defined as the maximum oxygen concentration at which a material passes NASA-STD-6001 Test 1 [2,3]. Using upward and downward flame spread tests with Nomex III in 1 atm Klenihenz and T'ien [1] determined the LOI to be 24% for upward flame spread, and 28% for downward flame spread. Upward propagation LOI tests are also known was (ULOI). Using reduced pressure environments, Hirsch et al. [2] found that when pressure was reduced to 0.7 atm the ULOI for single layers of Nomex HT90-40 was less than 30%. And in concurrent flammability experiments using single layers of Nomex HT90-40, Olson et al. [3] measured the MOC to be 22% in 1 and 0 g, while the ULOI was determined to 25.4% in 1 g and 23% in 0 g.

In the present work we present experiments aimed to determine the effects of an external radiant flux, oxidizer flow velocity and oxygen concentration on the minimum conditions for concurrent flame spread over thin flame retarding fabrics. Concurrent flame spread is analogous to upward flame spread, with the only difference being that in the latter the forced flow velocity is replaced with a buoyant velocity. In concurrent flame spread the flame covers the solid fuel during the heating and pyrolysis process, which makes it faster and more hazardous than opposed flame spread. For this reason, the concurrent flame spread configuration was selected for the present experiments. Two FR fabrics, Nomex HT90-40 and a Nomex/Nylon/Cotton fabric blend were used for the experiments. Both are materials are used in astronaut space suits, and other earth fabrics such as firefighter clothing and race car driver suits. Nomex is a family of aromatic polyamide fibers that create a strong flexible polymer chain with a high degree of heat resistance. In normal atmospheric conditions Nomex does not melt or drip but chars when exposed to high temperatures [6], which contributes to its FR characteristics.

2. Apparatus configuration

The experiments are conducted in the apparatus shown schematically in Fig. 1. It consists of a small-scale combustion wind tunnel 560 mm