Flame Spread Characteristics
of Fire Retardant Fabrics

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1   Introduction

The determination of the flammability characteristics of fabrics, both non-fire retardant (NFR) and fire retardant (FR), is important for fire safety purposes. Flammability testing of these materials is often conducted in standard temperature and pressure (STP) conditions [1-5]. However, there are situations where the determination of the flammability of fabrics in different environments is also important. An example is a fire in a spacecraft environment which 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. Thus, there is a practical interest in studying the flammability of fabrics in ambient conditions expected in spacecrafts.

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 Refs. [6-8] regarding the limiting oxygen concentrations for flame spread in FR fabrics and thin plastics. Upward and downward flame spread tests using Nomex III [6] determined the limiting oxygen index (LOI) in 1atm to be 24% for upward flame spread, and 28% for downward flame spread, when pressure was reduced to 0.7atm the upward LOI (ULOI) for single layers of Nomex HT90-40 was found to be <30%[7]. Concurrent flammability experiments using Nomex HT90-40 found the LOI to be 22% for both normal gravity and microgravity [8].

In the present work we introduce a testing methodology to determine the effect of an external radiant flux on the minimum oxygen concentration for concurrent flame spread over thin flame retarding fabrics. Results are presented for Nomex HT90-40

2   Apparatus Configuration

The experimental apparatus is shown schematically in Fig. 1. It consists of a small-scale combustion wind tunnel 560mm long with a rectangular cross-section 127mm by 100mm. The floor of the tunnel is made up of a 3.2mm aluminum plate covered by a 1.6mm ceramic insulation sheet. The bottom surface of the tunnel has a 50.8mm by 152.4mm rectangular cutout section located 158.8mm from the

inlet section of the tunnel. Test samples are mounted into the rectangular cutout section and sit flushed to the bottom surface of the tunnel. Sidewalls of the tunnel are made of 6 mm quartz windows for optical access, and the top surface of the tunnel is fitted with two parabolic radiant heaters (Research Inc., Eden Prairie, MN). The radiant heaters were positioned so that a decaying radiant flux was imposed over the fabric surface (Fig. 3). The radiant flux has a maximum value ($q"_{MAX}$) at the leading edge and decays with increasing distance away from the leading edge. Similar to ASTM E1321[3], the decaying heat flux distribution allows determining the minimum heat flux required for flame spread ($q"_{MIN}$) by recording the radiant flux corresponding to the position where flame spread stops. Mixtures of house compressed air and compressed oxygen are used to produce a gas flow of a given velocity and oxygen concentration. Copper calorimeters placed underneath the samples are used in some tests to determine the protection characteristics of the fabric to an external radiant flux.
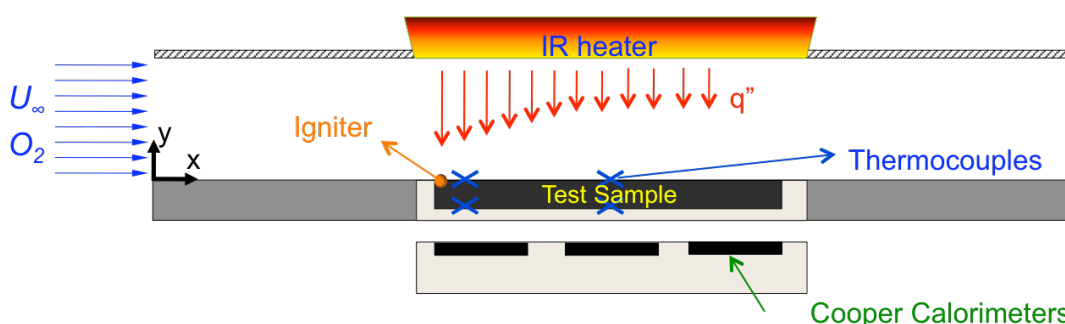

Figure 1. Experiment Schematic

Sample dimensions were chosen in accordance to 16 C.F.R. Part 1610 [1], which stipulates the methodology for testing flammability of clothing textiles sold in the United States. Temperatures in the surface and back surface of the fabric sample were measured using type-K thermocouples inserted at the leading edge and center of the test specimen. Although special attention was given to ensure proper contact between the thermocouple bead and the fabric surface, the recorded temperatures are only an approximation of actual surface temperatures. Ignition is accomplished using a Kanthal wire weaved across the upstream edge of the sample. All tests were conducted with a single layer of Nomex HT90-40 (Stern and Stern Industries Inc., Hornell, NY).

3   Experimental Procedure

Tests were conducted to determine the minimum oxygen concentration (MOC) for concurrent flame spread in radiantly heated fabric samples. A test begins by adjusting the oxidizer flow velocity and oxygen concentration using a calibrated flow bench. The flow bench allows conducting experiments with an oxidizer flow velocity ranging from 0.5 to 1.5 m/s and oxygen concentrations up to 35% by volume. Two variations of the experiments were conducted depending on the duration of the externally applied heat flux. In one case the external radiant flux was used to preheat the sample only, but it was turned off just prior to ignition so that the spread of the flame occurs only over an elevated temperature sample. In the second set of testes the radiant flux was kept on during the whole test. Fig. 2 presents a visual timeline of the sequence of events used in the two sets of experiments

3.1.Preheating Heat Flux Experiments

At the start of the test, the gas flow is adjusted; the radiant heaters are turned on and allowed to irradiate the test sample until steady state is reached (usually 180s after the start of a test). At this point the surface temperature of the sample attains a decaying profile from the upstream edge of the sample. Once the sample's surface temperature reached steady state, the igniter wire was energized and the

radiant heaters turned off. Flame spread was determined visually until no propagation was observed.

3.2. *Continuously Applied Heat Flux Experiments*

After the start of the test, the parabolic strip heaters are turned on allowed to irradiate the test sample for the entire duration of the experiment. The igniter wire was energized once the sample's surface temperature reached steady state
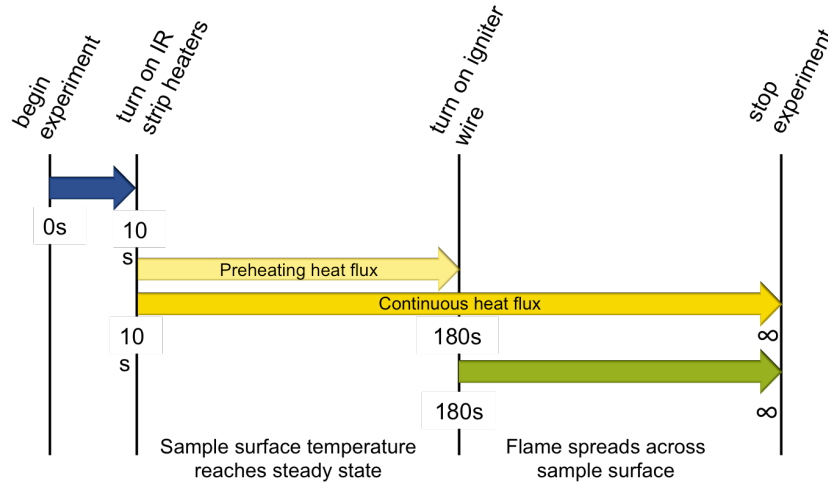

Figure 2. Experiment sequence timeline

The minimum heat flux for flame spread (q''_{MIN}) is obtained by relating the flame spread distance to the heat flux at the surface of the sample using the known heat flux distribution depicted in Fig. 3.
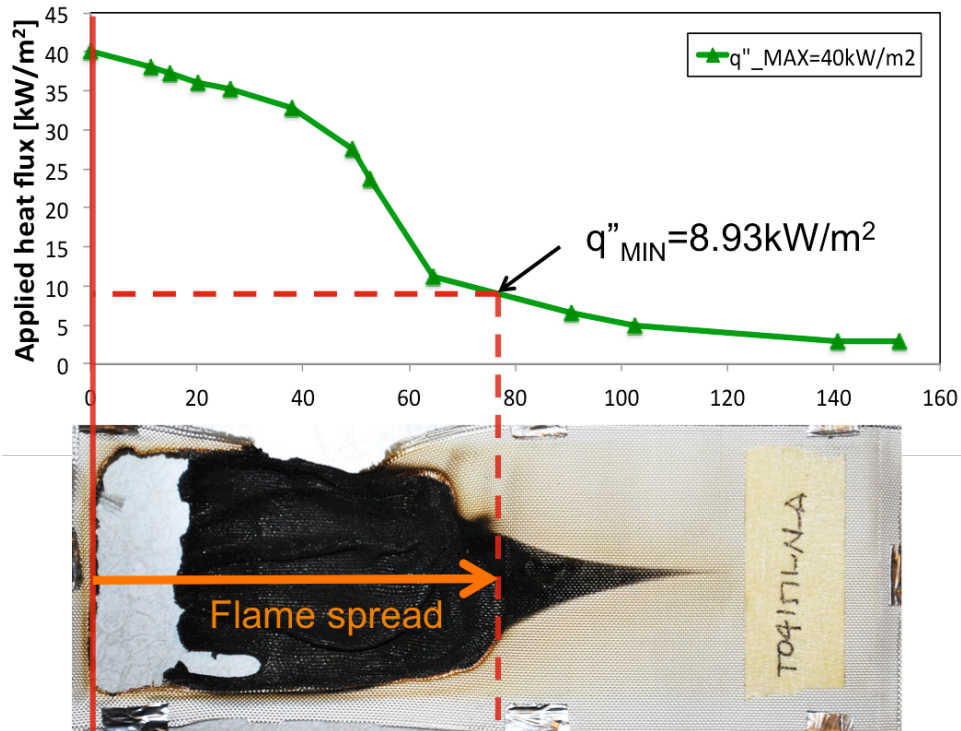

Figure 3. Relationship between flame spread length and minimum heat flux for flame spread.

4   Results

Experiments were conducted with maximum radiant heat fluxes at the sample leading edge ($q"_{MAX}$) ranging from 25kW/m^2 to 40kW/m^2, and oxygen concentrations ranging between 21% and 35% by volume. For all experiments the oxidizer flow velocity was constant at a value of 1.0 m/s.

In the preheating heat flux experiments flame spread was consistently observed when [O_2] was equal to or greater than 30%, and the radiant flux applied during preheating (q") was approximately greater than 33 kW/m^2. No significant flame spread was observed for lower values of the radiant flux or oxygen concentration. Although the samples ignited in concentrations below 30% oxygen, the experiments conducted showed no significant flame spread. Ignition for these points is believed to be due to igniter wire influence. Results in Fig. 4 show the conditions for which flame spread was observed, points with no significant flame spread were omitted. The data points indicate the boundary between flame spread and no flame spread.
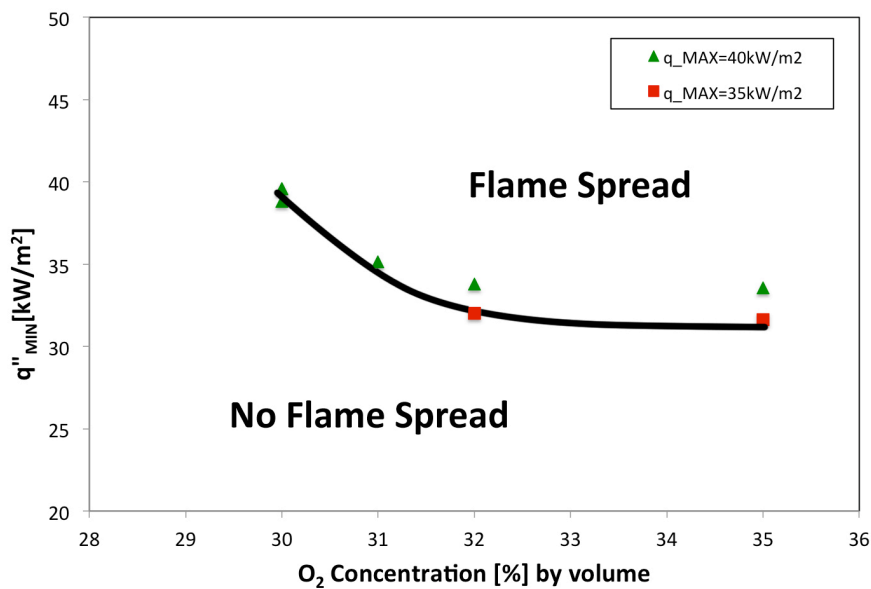

Figure 4. $q"_{MIN}$ vs. [O_2] for flame spread during *Preheating Heat Flux*

The results for tests under the continuously applied radiant flux are presented in Fig. 5. The data points indicate the boundary between flame spread and no flame spread. Results show that $q"_{MIN}$ depends on oxygen concentration, as O_2 concentration increases the value of the minimum heat flux for flame spread decreases, the shaded area in Fig. 5 represents the region where flame spread occurs for continuously applied radiant flux.
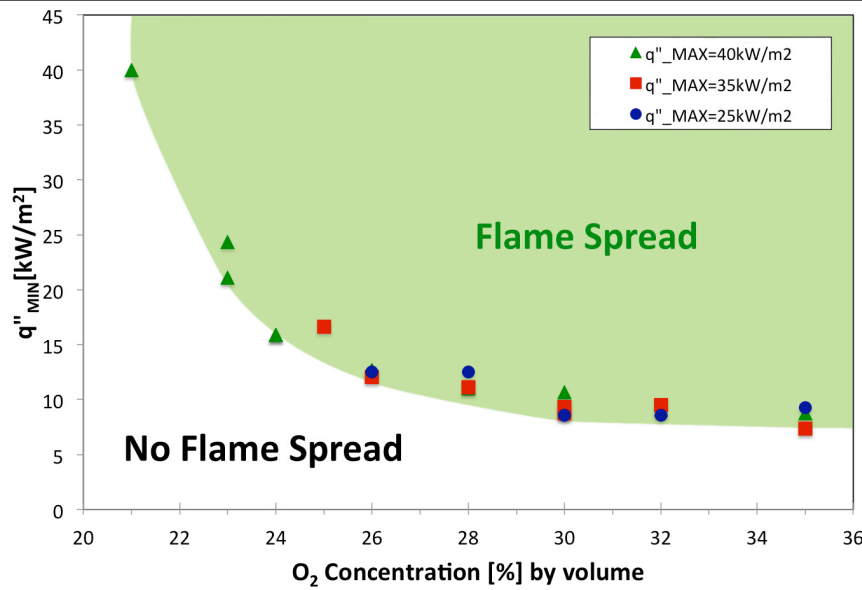
Figure 5. q"$_{MIN}$ vs. [O$_2$] for flame spread during *Continuously Applied Heat Flux*

5 Discussion

The results shown above can be approximately explained in terms of the flame spread rate equation proposed by Fernandez-Pello [9].

$$Vf = \frac{c\left[\left(c_1 k_g \rho_g c_p u_\infty / l_p\right)^{1/2}\left(T_f - T_p\right) + \dot{q}"_{fr} + \dot{q}_e - \dot{q}"_{rs} - \dot{q}"_{ret}\right]}{\rho_s c_s s\left(T_p - T_o\right)} \tag{1}$$

The effect of the fire retardant is complex but can be approximately incorporated as a negative term (q"r$_{et}$) in the numerator of Eq. 1.The equation provides a simple expression that helps explaining the experimentally observed effects of the externally applied heat flux and high oxygen concentration in the flame spread rate of Nomex.

During the *Preheating Heat Flux Experiments* the only terms affected in Eq. 1 are the flame temperature (T$_f$) and the solid temperature (T$_o$). Preheating the sample until it reaches steady state increases the value of T$_o$ up until ignition is induced, at which point the radiant flux is turned off and T$_o$ starts decaying. Nonetheless, the net effect is an increase in T$_o$ with respect to the initial fabric temperature. Increasing the oxygen concentration has a direct effect in flame temperature. As O$_2$ concentration increases, T$_f$ increases because more oxygen is available for the combustion process and a smaller volume of nitrogen has to be brought up to equilibrium with the flame temperature. Only for O$_2$ concentrations greater than 30% and q">33kW/m^2 the increases in T$_f$ and T$_o$ are large enough to overcome the heat losses due to surface re-radiation and fire retardant effects so that flame spread occurs.

For *Continuously Applied Heat Flux Experiments*, the external radiant flux term (q"$_e$) in Eq. 1 depends on the location along the sample. In addition, the solid temperature will increase and remain constant throughout the rest of the experiment. Also an elevated oxygen concentration will increase flame temperature. The end effect is an increase in the value of the numerator and a decrease in the numerator of Eq. 1, which ultimately leads to an increase in the flame spread rate. Since the solid temperature is larger than in the preheating experiments and the radiant flux is kept on, it is understandable that flame spread occurs under lower radiant fluxes and oxygen concentrations under

the continuous radiant flux conditions than simply pre-heating the solid

6 Conclusion

The results obtained here indicate that the LOI of fire retardant fabrics is dependent on the magnitude of a radiant flux applied to their surface, decreasing as the radiant flux is increased. This result may have relevant consequences in the design of fire protective clothing for individuals that may be exposed to specific environments such as those encountered in spacecrafts.

Acknowledgements

References

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