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Review article

Textile flammability research since 1980 – Personal challenges and partial solutions

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ABSTRACT

This paper reviews the changing textile flammability research themes within the author's research group over the last 35 years and which reflect those of the academic and research communities often influenced by industrial and societal pressures. For instance, ignition studies undertaken in the early 1980s together with the effect of textile fabric structural variables reflected academic contemporaneous interests as well as those related to real hazards posed, for example, by nightwear fabrics. Also, work undertaken to study flame retardant mechanisms, especially on cotton substrates, reflected the need for commercial interests to more fully understand their chemical treatments largely developed during the 1960–1970 period.

During the subsequent 1980 period, the ecotoxicological concerns regarding flame retardants in general started to develop which continue with even greater vigour at the present time. Thus research effort focussed on developing low or zero formaldehyde treatments for cotton and alternatives to bromine-based flame retardants present in back-coatings applied to furnishing fabrics which also promoted interest in the study of novel intumescents. By the 1990s, the demonstration of the potential of nanocomposite polymers with improved fire performance raised the possibility of novel textile flame retardant developments with improved environmental sustainability. More recently, nanotechnological engineering of fibre surfaces to promote improved substrate flame retardancy has created a significant literature.

In conclusion, it is evident that while most of this research has improved scientific knowledge, its translation into novel commercial opportunity has been more elusive and this will probably remain the case as we move into the next ten years or so where the environmental challenges of reducing real or apparent ecotoxicological properties of flame retardant textiles remain.

1. Introduction

Comprehensive reviews [1,2] have critically reviewed the research period up to about 1980 during which period most of the presently used commercial flame retardants for fibres and textiles were developed and references within these direct the reader to more contemporary specific reviews of particular flame retardant types. Specifically, these include the established durable and flame retardant treatments for cotton and wool fibres as well as those additives and comonomers introduced into both regenerated (e.g. viscose) and synthetic (notably polyester, polypropylene and the modacrylics) fibres. During the years 1975–1980 the back-coatings used in a number of applications, including furnishing fabrics were developed and their popularity has derived from their having little effect on fabric face aesthetics as well as their extreme cost-effectiveness [3,4].

The history of the development of these commercially-acceptable flame retardants for fibres and textiles during this period has been reviewed by me quite recently [5] and I used the descriptor "golden era" to signify the importance of these years. While other reviews have considered developments since that time [4,6,7], they all show that few new commercial developments since 1980 have been achieved. The period 1979–2013 coincides with research undertaken by my own research group, often in collaboration with that of Denis Price, previously at the University of Salford and now at Bolton.

This review covers research undertaken during this period within my own research group and is not meant to be a comprehensive overview of all textile flammability research undertaken. However, it does reflect the changing interest world-wide within flame retardant textiles and the industrial flame retardant industries that supported this research. Working with colleagues, the

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following major areas have been studied in the almost chronological order:

- Ignition studies and burn hazards
- Effects of textile structural variables on burning behaviour
- Flame retardant textile mechanisms: pyrolysis, gas emissions and smoke
- Novel intumescent textiles
- Environmentally sustainable flame retardant textiles and novel back-coating systems
- Effect of dispersed clays in fibre-forming polymers.
- Burning behaviour of flame retarded textiles subjected to high heat fluxes.
- Surface treatments based on nanotechnology

These studies in the majority of cases were undertaken within externally-funded projects, most with some level of industrial input and so they reflect contemporary interest within the international flame retardant textile community. It is instructive to note that most industrial sponsors were manufacturers of flame retardants and treatments and rarely synthetic fibre producers and so the review reflects this bias. Furthermore, the paper will discuss the challenges and achievements, as well as failures, during this time although the lack of definitive success is all too often accompanied by increased understanding of the problems being addressed and sometimes incremental improvements in commercial products and processes can and have followed.

2. Ignition and textile burn hazards

Ease of ignition is a feature of many standard textile flammability tests for obvious reasons and yet the underlying science is still poorly understood. While often simply determined as the time to ignite of a fabric subjected to a standard flame, often a simulant of a simple match flame (e.g. BS ISO 6940), other measures of ease of ignition include either the time to ignite when exposed only to a defined radiant heat flux or the temperature at which a sample ignites when exposed to such a source [8,9]. For polymeric materials generally, the Setchkin furnace (ASTM D1929) is a well-established and simple means of determining the ignition temperature with results quoted by many authors [10]. Since the advent of the cone calorimeter, it is well-established that the common textile fibres like cotton, viscose and polyester, for example, will ignite when exposed to heat fluxes in the range 20–25 kW/m^2 [11]. Flame retarded textiles usually require higher heat fluxes in the range 30–50 kW/m^2 and so for decorative flame retardant textiles attached to wall and other internal panels in commercial aircraft, for example, they are tested under a heat flux of 35 kW/m^2 as defined in the aviation standard FAR 25.853 Part IV Appendix F for their ability not to spread fire using the Ohio State University (OSU) calorimeter [12] (see also Section 8).

The question of ignition arose in my own research over 35 years ago while starting to investigate the comparative flame retardant mechanisms of a range of commercially flame retarded cotton fabrics (see Section 4 below). Initial studies used thermal analysis and in particular, differential thermal analysis (DTA) of these fabrics under flowing air conditions showed that for pure bleached cotton, above a critical air flow rate, the sample did not simply pyrolyse oxidatively but spontaneously ignited [13]. Subsequent work, which studied the effect of oxygen concentration and the effect of flame retardants present, enabled activation energy of cellulose oxidation, E_{ox} values to be calculated [14] as well as activation energies of pyrolysis, E_p [15]. Table 1 summarises results from these experiments.

Table 1
Activation energies of cellulose pyrolysis, E_p, and oxidation, E_{ox}, during spontaneous ignition.

Sample	E_p, kJ mole^{-1}[a]	E_{ox}	Ref.
Cotton	146	215	[13,14]
Ammonium polyphosphate-treated cotton (2.2 %P)	145	270	[15]
Proban®-treated cotton (2.9 %P)	230	536	[15]

[a] Under 21 vol% oxygen (air) conditions.

Here it is clear that while the presence of a flame retardant may have little or considerable effect on the pyrolysis activation energy, ease of oxidation is considerably reduced relative to when none is present.

Later, renewed interest during the late 1990 period occurred within the EU especially [16], because of concern regarding the burn hazard provided by lightweight nightdress fabrics [17] (and which led to the standard EN 14878:2007) caused us to undertake work, part funded by the British Burns Association, to investigate the ease of ignition of a range of fabrics by both a modified Setchkin furnace method [18] and cone calorimetry [11]. Using the former method, it was proposed that the sensitivity of ignition time, t, to oven temperature, T, will relate to ease of ignition and hence the potential hazard of causing severe burns. Thus extrapolation of time-to-ignition versus $1/T$ each plot for each fabric enabled the ignition temperature at $t = 0$, $T_{ig(t=0)}$ to be defined (see Table 2) [18]. The highest $T_{ig(t=0)}$ values should represent reduced sensitivities to ignition which suggests that the more flammable fabrics cotton and polyester-cotton present higher ignition hazards than lightweight silk and wool. The apparently lower heavy weight silk $T_{ig(t=0)}$ value is difficult to explain and could be anomalous (see below).

Later work [11], described a method of reproducibly measuring the ignition and heat release properties using cone calorimetry in which the thermally thin, unstable fabrics were superimposed with a thin wire grid assembly. This work showed the effect of heat flux on the ignition characteristics of these same fabrics from which FIGRA (fire growth index) measurements under 50 kW/m^2 were determined and listed in Table 2. The lower the FIGRA rating, the lower is the burn hazard from a given fabric once it is ignited. The hazard ratings listed suggest that again wool is the least hazardous fabrics in terms of ease of ignitability and burn propensity. FIGRA results for heavy weight silk are intuitively sensible unlike the value its respective $T_{ig(t=0)}$ value.

However, it must not be forgotten that ignition temperatures of bulk flammable materials can be significantly less than values

Table 2
$T_{ig(t=0)}$ and FIGRA values for typical nightdress fabrics with respective hazard rankings in parentheses (1 = lowest hazard) [11,18].

Fabric	$T_{ig(t=0)}$, °C	FIGRA (at 50 kW/m^2 heat flux)
(i) Light-weight cotton (87 g/m^2, 0.17 mm thick)	480 (6=)	27.0 (3)
(i) Heavy-weight cotton (180 g/m^2, 0.30 mm thick)	480 (6=)	27.0 (3)
(i) Polyester/cotton (65:35,105 g/m^2, 0.16 mm thick)	574 (3=)	29.4 (4)
(i) Polyester/cotton (55:45, 118 g/m^2, 0.26 mm thick)	574 (3=)	–
(i) Acrylic (118 g/m^2, 0.26 mm thick)	–	35.0 (5)
(i) Light-weight silk (71 g/m^2, 0.14 mm thick)	909 (1)	–
(i) Heavy-weight silk (174 g/m^2, 0.30 mm thick)	505 (5)	9.5 (1)
(i) Wool (173 g/m^2, 0.33 mm thick)	746 (2)	18.0 (2)