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Physiological comfort and flame retardancy of fabrics with electrostatic self-assembled coatings

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ABSTRACT

Simultaneous improvement of flame retardancy and physiological comfort of clothing fabrics has not been studied before. One of the probable reasons for this is the complexity of dynamic processes involved. This work is a preliminary effort to understand various parameters involved in combining these two facets of fabrics. For this purpose, polyester fabrics are coated with branched polyethylenimine (BPEI) and sodium montmorillonite (smectite clay) via electrostatic self-assembly approach. The effect of their concurrent presence in different concentrations (variation of number of bilayers) on thermo-oxidative properties and flame retardancy behavior as well as physiological comfort (in terms of wicking, moisture management, and air permeability) of polyester has been assessed. The obtained results have shown the efficiency of the electrostatic self-assembly process in improving both facets. This work provides the foundation and knowledge for further development of effective coating systems with a multi-functional approach in the textile industry.

1. Introduction

Flame resistant textiles are important not just for fire fighters, laboratory, police or military personnel, but also in the sports industry (for example, car/motor bike racing). In these applications, a major concern during fire incidents is the associated thermal injury. It is shown that exposure to a radiant heat flux of 4 kW/m^2, which is quite common in room corner and small-scale fires, causes second-degree burns to bare skin in 30 s [1,2]. However, most serious burns are often related to ignition of clothing than if no clothing had been worn, particularly when the initial fire is small or of short duration [3]. Also, ignition of the clothing results in a higher total body surface area burn, which increases third degree burns. Apart from clothing, other factors that influence the severity of burn injury include intensity of incident heat flux, exposure time, and combustion/pyrolysis products of fabrics [4].

Similar to bulk polymeric materials, textile fibers and fabrics require flame retardants (FR) like halogen- or to some extent phosphorous-based compounds to achieve satisfactory flame resistance. Their usage is often linked to eco-concerns as many of them ultimately yield persistent organic pollutants and generate corrosive/toxic combustion products [5]. Textiles, as they are often washed, flame retardant additives can leach out of the fabric and into the environment increasing the risks associated [6,7]. This is another reason why even some of the non-toxic flame-retardants cannot be used in these applications. For instance, lack of durability of boron-based flame-retardants restricts them to non-aqueous washing [8].

Further, personnel handling work involving risk of fire hazards are expected to put on fire resistant clothing as long as they are on duty. Therefore, a key performance criterion of protective clothing is physiological comfort of the wearer. This will significantly influence the efficiency at which he or she operates [9–13]. Considering that temperature changes in a (hygroscopic) fabric due to water vapor sorption can be as high as 15 °C [1], the differences in perceived comfort are expected to be significant. Temperature rise and higher body sweat can cause discomfort and heat stress to the wearer as well as skin damage from chafing. It is well known that in hot and humid conditions, trapped moisture may heat up and lead to diminished performance; while in cold conditions, trapped moisture results in temperature drop and cause hypothermia. In summary, air permeability, surface texture and moisture management of fire resistant fabrics are important. Moisture management indicates the ability of a garment to transport moisture away from the skin to the garment's outer surface and subsequently to the environment. That is, it involves wettability, spreading ability and imbibition of moisture/sweat on/through the fabric.

To render a fabric flame retardant, one of the approaches is to modify individual fibers [14]; another, and a widely used strategy is coating at the fabric level. Different types of coatings have been used to impart flame retardant properties to fabrics [15–22]. Some of these are based on intumescent systems [17,18], sol–gel based silica [19,20], polyphosphazenes [21], and phosphoramide nanoparticles [22]. Very few studies used polymer nanocomposite coatings as flame retardant compositions on fabrics, which is the focus of the current work.

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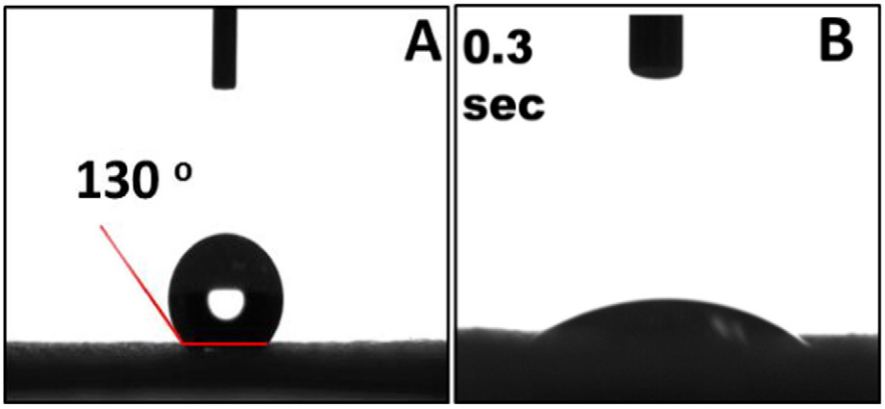

Fig. 1. Representative water contact angle images for (A) neat fabric and (B) NaOH pre-treated and all coated fabrics.

For this process, a facile electrostatic self-assembly process is used [23–25]. In a typical process, fabric is alternatively dipped into positively and negatively charged (dilute) aqueous solutions. Electrostatic interactions between the charged layers drive the adsorption and assembly process. For more details on this process, please refer to Li et al. [26]. Nonetheless, to-date, there are no reports discussing how the modifications to a fabric affect its moisture management and breathability properties. This is in spite of considerable efforts to develop smart fabrics [27]. From an application viewpoint, both these aspects (physiological comfort and flame retardancy) are equally important. Hence, this work is a first attempt in that direction.

2. Experimental section

2.1. Materials

Polyester fabric of mass, 174 g/m^2, was locally purchased in Singapore and rinsed with deionized (DI) water (18.2 Ωcm^{-1}) prior to use. It has a circular knitting and single jersey structure along with stitch density of 18.1 wales/cm and 24.8 courses/cm. Cloisite® NaMMT clay with formula unit $Na_{0.65}[Al,Fe]_4Si_8O_{20}(OH)_2$ was supplied by BYK Additives & Instruments, Singapore. NaMMT was added to DI water and mechanically stirred for a minimum of 12 h to produce 1 wt.% of exfoliated anionic deposition suspension. Base pH 6 for NaMMT suspension was adjusted to pH 10 through addition of 1 wt.% of NaOH solution. Cationic deposition solution was prepared by dissolving BPEI (M_w, 25,000 g/mol and M_n, 10,000 g/mol) in deionized water and magnetically stirring the solution for at least 12 h. BPEI was purchased from Sigma-Aldrich, Singapore. Base pH 9 for BPEI solution was adjusted to pH 7 using 0.1 wt.% hydrochloric acid prior to coating on polyester fabric. In another set of experiments, polyester fabric was pre-treated with alkali solution (10 wt.% NaOH). This was carried out by immersing the fabric in alkali solution for ~15 min at room temperature. This was followed by thorough washing to remove excess NaOH (as monitored by pH of DI water used for washing), rinsing and overnight air drying at room temperature.

2.2. Electrostatic self-assembly procedure and characterization

Polyester fabrics (neat and NaOH pre-treated) were alternatively immersed in 0.1 wt.% BPEI suspension and 1 wt.% NaMMT suspension. After each immersion step, substrates were washed with deionized water for 1 min to remove poorly adsorbed (and sometimes, excess) nanoparticles. Immersion duration for the first 5 bilayers was kept at 5 min to ensure stability and uniformity of the assembly. For subsequent bilayers, substrates were immersed only for 1 min. Every immersion cycle corresponds to one bilayer of assembly. Washing solutions were replaced after every 5 bilayers, while the suspensions were manually stirred and pH was checked to ensure invariability throughout the deposition process. Subsequently, fabrics were oven dried at 60 °C for 5 h.

Wettability of neat and coated polyester fabrics was characterized using goniometer (Data Physics Contact Angle System, OCA 15 Pro). Vertical wicking tests were carried out on fabric strips of 20 cm × 2.5 cm suspended in distilled water according to American Association of Textile Chemists and Colorists (AATCC) test method 197–2013 (Method B). Wicking distance of water is taken over a period of 30 min. Moisture management measurements were carried out on Moisture Management Tester M290 according to AATCC test method 195–2009 to assess liquid moisture transportation through fabrics. Further, air permeability measurements of neat and coated fabrics were carried out by using ASIAN Air Permeability Tester and based on ASTM D737-04(2012).

Morphology of fabrics was analyzed using JEOL 5410 scanning electron microscope (SEM) and JEOL 6340 F field emission scanning electron microscope (FESEM). Structural chemistry of fabric surface was also assessed using attenuated total reflectance (ATR) mode of Spectrum GX (Perkin Elmer) Fourier Transform Infrared spectroscopy (FTIR). All spectra were acquired using 32 scans and 4 cm^{-1} resolution. Pore sizes and their distribution in different fabrics were measured using PMI Capillary Flow Porometer CFP-1500A. Galwick (propene, 1,1,2,3,3,3-hexaflouro, oxidized and polymerized) with surface tension of 15.9 dynes/cm was used as the wetting agent. All test samples were conditioned at a temperature of 21 ± 1 °C and relative humidity of 65 ± 2% for 24 h in accordance to ASTM D1776/D1776M-15.

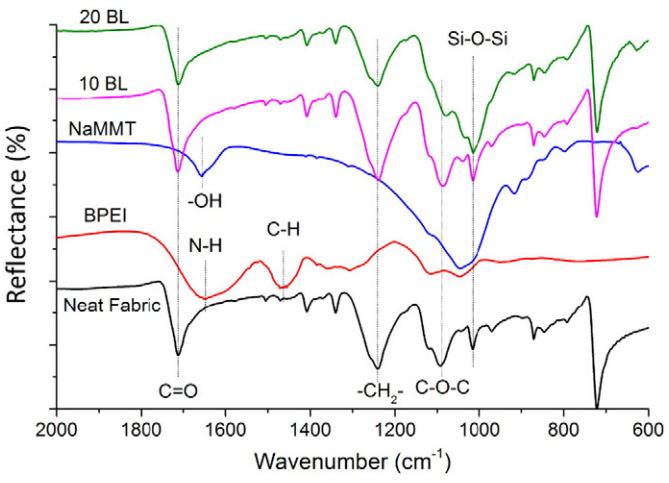

Fig. 2. FTIR spectra of neat fabric, BPEI, NaMMT and untreated-coated fabrics (10 and 20 bilayers). BL in the figure indicates bilayers.