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A New Approach for Improving Flame Retardancy of Automotive Interior Upholstery

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ABSTRACT

This study presents the flame retardant (FR) performance of chemically treated automotive upholstery fabrics using two different impregnation methods of Resin Transfer Molding (RTM) and supercritical carbon dioxide ($scCO_2$). Referring to the related standards, untreated seat fabric obtained from seat upholstery of a bus (neat fabric, NF) and treated fabric samples underwent burning rate (BR) and limiting oxygen index (LOI) tests to compare effect of treatment and impregnation methods on FR performance. Thermal analysis was also conducted on the samples considering onset degradation temperatures and char yields. The results showed that BR and LOI of all samples were in acceptable range and treatment provided enhancement in FR performance of NF. The treated sample using $scCO_2$ method gave the highest LOI value of 32% and the lowest BR of 21 mm/min subtending to 18.5% increase in LOI and 30% reduction in BR compared to those of NF. The performance of treatment in RTM was worse than that of $scCO_2$ and better than that of NF. The results confirm that both treatment and methods used in this study give promising results for safety against fire in transportation vehicles.

Otomotiv İç Döşemelerinin Güç Tutuşurluğunu Geliştirmek İçin Yeni Bir Yaklaşım

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Anahtar Kelimeler
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ÖZ

Bu çalışmanın amacı, RTM ve $scCO_2$ olmak üzere iki farklı yöntem kullanılarak otomotiv kumaşlarının alev geciktirici performansını arttırmaktır. Bir otobüsün koltuk döşemesinden elde edilen kumaş numuneleri yanma hızı (BR) ve sınırlayıcı oksijen indeksi (LOI) testlerine tabi tutulmuşlardır. Numuneler üzerinde termal analiz de yapılmıştır. Sonuçlar, tüm örneklerin BR ve LOI değerlerinin uygun aralıkta olduğunu ve kimyasal iyileştirmenin NF'nin FR performansında artış sağladığını göstermiştir. $scCO_2$ yöntemi kullanılarak işlenen numune, NF'ye kıyasla, %32 LOI değeri (%18.5 artış) ve 21 mm/min BR değeri (%30 azalış) ile en iyi performansı göstermiştir. Elde edilen bulgulara göre, bu çalışmada kumaşa uygulanan yöntemlerin ve kimyasal işlemin ulaşım araçlarında yangına karşı güvenlik açısından umut verici sonuçlar verdiği gözlemlenmiştir.

1. INTRODUCTION

Textile materials used in everyday life are either originated from natural sources or derived from synthetic compounds. The production rate of synthetic compounds is roughly 55% higher than that of natural fibers due to their superior features such as low-cost, strength, flexibility, wear resistance, etc. On the other hand, the organic structure of synthetic fibers paves the way for tendency of easily catching fire and fast spreading of flame due to melt dripping in case of a contact with the fire source [1-3].

Technical textiles have a broad range of usage area in automotive industry such as interior upholstery, floor and pillar coverings, airbags, seat belts, tires, filters etc. accounting for approximately 20-25 kg of textile usage in an average passenger car [4-7]. As per customers' demands, automotive textiles should meet various requirements. For instance, it is expected that seat fabric of a vehicle should perform high flame retardancy, resistance to abrasion and sunlight as well as stain repellency [1,2,8,9]. On the other hand, seat belts and tires require high strength materials and thus, polyester fibers and high abrasion resistance polyamide fibers are often used in transportation vehicles [10,11]. The fabric classification with GSM (g/m^2) values used as seat upholstery of a vehicle is tabulated in Table 1 [12].

Table 1. Fabric types for vehicle seat upholstery

Fabric type	GSM (g/m^2)
Plain woven	200-400
Plain woven velvet	360-450
Warp-knitted	160-340
Raschel double needle bar knitted	280-370
Circular knitted	160-230

In the late 1960s and early 1970s, in seat coverings, automotive industry had used Nylon-6, acrylic, wool and polyester fibers instead of polyvinylchloride. However, there are drawbacks in usage of nylon, polyacrylonitrile fiber and wool in automotive coverings due to high decomposition rate in sunlight, limited abrasion resistance and high cost, respectively. In this context, polyester fabric steps forward for seat coverings of vehicles [8].

The seat covering is primarily constructed of polyurethane foam cushion which is laminated to the fabric in a variety of ways [13-19]. Among these, flame lamination method (Figure 1) is commonly used for lamination of foam and seat fabric rather than dry lamination with thermoplastic adhesive due to drawbacks of the latter in terms of high cost, low process speed and requirement of chemical glue during the process.

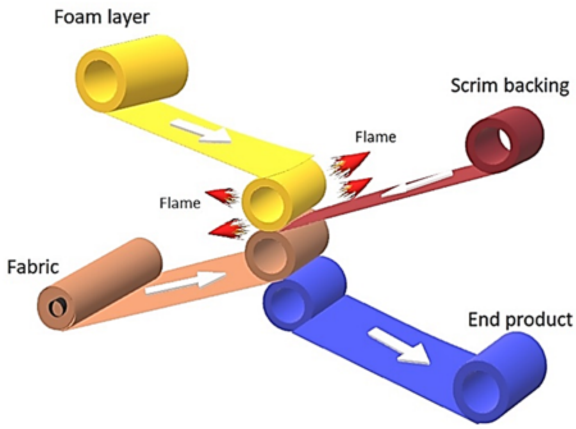

Figure 1. Flame lamination technique

Alternative fuel vehicles are now utilized in practically every kind of transportation, including cars, buses, heavy-duty trucks, trains, and airplanes. Currently, apart from explosive conventional fuels such as LPG and gasoline, latest technological advances in automotive technology focus on hydrogen fueled vehicles, ethanol fueled cars or electric vehicles with batteries capable of covering long ranges. However, certain alternative fuel cars may pose significantly greater risks in terms of flammability. For instance, a thermal runaway in an electric vehicle's battery caused by an overcharge, an electrical malfunction, an outside fire, or a heating source could emit hazardous fumes and perhaps cause an explosion. Explosions can take several forms such as detonation, boiling liquid expanding vapor explosion, gas tank rupture, and deflagration [20]. Thus, researches and utilization of flame retardant (FR) materials in transportation vehicles are very important safety factors for drivers and passengers. In this context, seat fabrics undergo several chemical processes [21–28] with various recipes to gain flame retardant specification. The conventional pad-dry-cure process (Figure 2), which involves dipping the fabric into the FR solution, padding to remove extra solvent, and then drying and curing the cloth, is widely used to insert FRs into cotton fabric. However, incorporation of FRs in this system may be a challenging issue [29]. Another way to incorporate molecules into textiles is by using a supercritical fluid. Supercritical fluids are extensively used as processing media for synthetic and biopolymers offering an alternative method for modification of natural cellulose [30]. They are also known with their cost-effective, environmentally-friendly, non-flammable, non-toxic, and high diffusion rate in organic material features. Moreover, supercritical fluids can minimize or completely do away with the need for water and organic solvents when dyeing or impregnating hydrophobic or hydrophilic substances into cotton fabrics [31,32]. scCO_2 has been commonly utilized in extractions, impregnations, drying processes, and coloring of textiles or polymers [33,34].

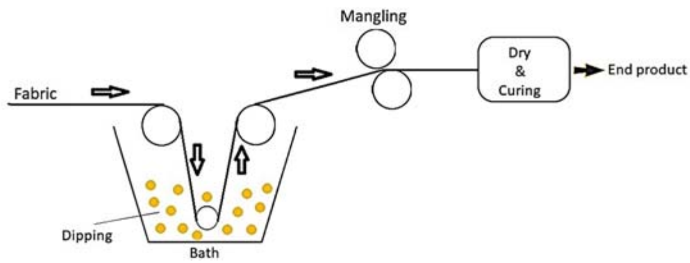

Figure 2. Pad dry-cure system

The lowest oxygen concentration required in an oxygen and nitrogen combination to sustain a material's blazing combustion is known as the limiting oxygen index, or LOI. It's stated as a volume percentage (vol%). The procedure entails setting up a sample vertically in a regulated environment and ignite the top of the sample using a burner. Combustible materials have LOI values of less than 21%, whereas self-extinguishing materials have LOI values of greater than 21, indicating that they require an external energy source to sustain their combustion at room temperature. One of the benefits of LOI is that it offers a repeatable and easy way to calculate a flammability index. In addition, the test apparatus is reasonably priced, and the sample quantity needed for testing is little [35]. The LOI can be found as shown below:

$$LOI (\%) = 100 \times [O_2] ([O_2] + [N_2]) \quad (1)$$

where; $[O_2]$ and $[N_2]$ denote the concentration of oxygen and nitrogen gas, respectively.

Resin transfer molding (RTM) is an effective way of impregnation of fabric with the chemical recipes in a rigid mold cavity [36]. Its foundation consists of an injection pump, a catalyst-resin storage system, and a mold where yarns are subjected to a high load pressurization process while bonding and reaction-accelerating components are mixed with resin catalyst [37,38].

Amphoteric aluminum hydroxide, $Al(OH_3)$, functions as a base in acidic media, creating a salt, and act as a Lewis acid in basic medium. Decomposition of $Al(OH_3)$ with an endothermic dehydration reaction at around 180°C and releasing water vapor in case of a fire makes it unique as FR additive. Furthermore, these metal hydroxide functions as powerful smoke suppressants to stop the combustion of polymer matrix materials [39-41].

This study aims to investigate the effect of two different methods of resin transfer molding and scCO_2 method on enhancing flame retardancy of automotive seat fabrics. In literature, to the author's knowledge, though there are several studies focusing on improving flame retardancy of fabrics, neither impact of scCO_2 and RTM method on reducing flammability of automotive interior upholstery nor their comparison have been established. Thus, it is expected that this study will be a good guide for automotive textile industry.

2. MATERIAL AND METHOD

The 100% polyester double-face knitted fabric samples (34 wales x 22 courses) with GSM of 45 g/m^2 were supplied from seat upholstery of a bus. ZnO nanoparticles (~50 nm, 99.9% purity, in powder), urea (99%) and aluminum hydroxide were purchased and used without any modification. The fabric samples were bleached and any contamination was removed before the treatment in RTM machine and $scCO_2$ reactor. In RTM machine (Figure 3), thoroughly mixed matrix (Table 2) at 140 rpm for 1 h was sent to the molding chamber by a specially made high pressure pump and compressed by hydraulic pistons at very high pressure of 170 bar (17 MPa) for good impregnation of fabric with the flame retardant mixture. The temperature of the treated fabric in the mold was at about 150ºC.

Table 2. Substance concentration in FR solution

Sample code	Definition	Substance fraction in treatment bath			
		ZnO nanoparticle	**$Al(OH_3)$**	**Urea**	**Deionized water**
NF	Neat fabric	-	-	-	-
TF-RTM	Fabric treated in RTM	1 wt%	20 wt%	10 wt%	69 wt%
TF-$scCO_2$	Fabric treated in $scCO_2$	-	-	-	-

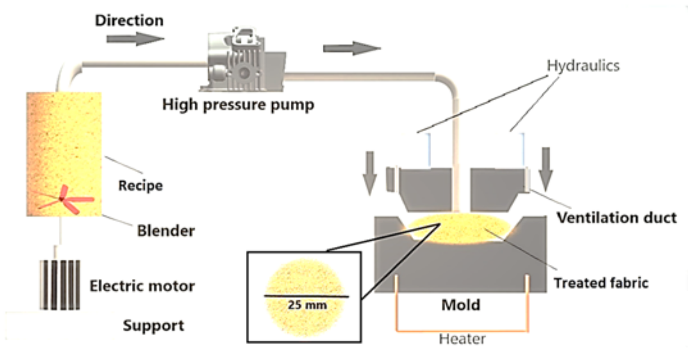

Figure 3. RTM experimental test rig

The temperature controlled $scCO_2$ reactor (Figure 4) consists of high purity carbon dioxide and purge pump. The fabric sample was immersed in the FR matrix and placed into the $scCO_2$ reactor in a fixed position. The temperature of the reactor was maintained at 100°C while the treated fabric was impregnated with $scCO_2$ for 2 h at pressure of 130 bar. Following a 10-min drying period at 110°C, the fabric samples were cured for 5 minutes at 140°C.

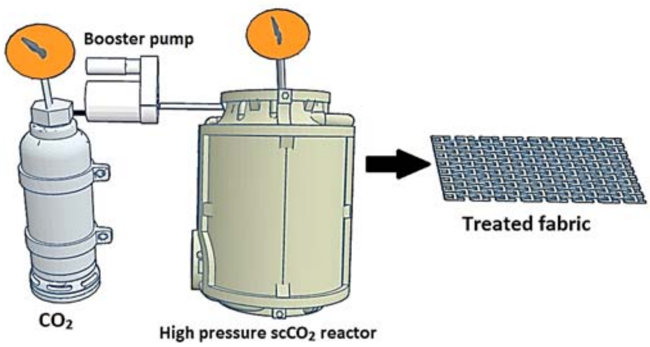

Figure 4. Illustration of $scCO_2$ method

The samples' ability to withstand flames was evaluated in accordance with ISO 3795 [42]. In this method, the samples were positioned horizontally in a U-shaped holder and free-ends were exposed to low-energy flame for 15 seconds (Fig. 5). The purpose of this test was to measure the rate of horizontal burning of textile composite structures found in transportation vehicles. The test detected whether and when the flame went out or how long it took for the flame to go a predetermined distance [7,43].

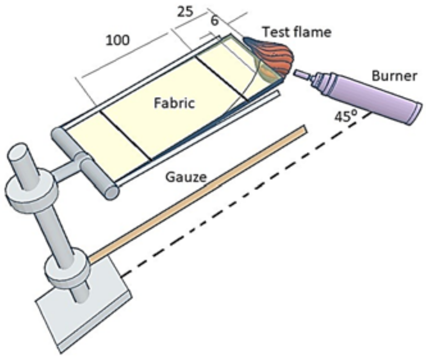

Figure 5. Schematic of the flammability test

In LOI tests, the fabric sample was inserted vertically into a glass cylinder, and the top edge of the specimen was ignited. To maintain the burning flame, a steady stream of a mixture of oxygen and nitrogen was supplied from the chamber's bottom. The oxygen content is gradually lowered until the sample extinguishes (Figure 6).

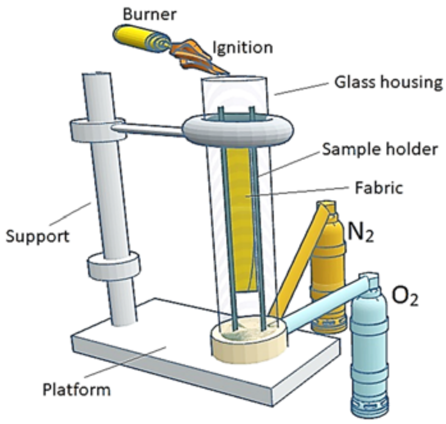

Figure 6. Fabric LOI test set-up

3. RESULTS AND DISCUSSION

BR and LOI were considered as flame retardancy performance of NF and treated fabrics in RTM (TF-RTM) and $scCO_2$ (TF-$scCO_2$). NF was taken as control sample and comparison was made in terms of aforementioned parameters. As shown in Figure 7, burning rate values of all samples were below 100 mm/min which is the upper limit for automotive technical textiles [44]. Thus, it can be said that burning rate results were in acceptable range for the automotive industry. The BR results present that the chemical treatment using two different methods provided considerable reduction in BR of fabric samples compared to that of NF. The average BR of TF-RTM was 25 mm/min subtending to a roughly 15% reduction compared to that of NF. However, TF-$scCO_2$ showed better performance in terms of BR corresponding to an average of 21 mm/min which is 16% lower than that of TF-RTM and 30% lower than that of NF.

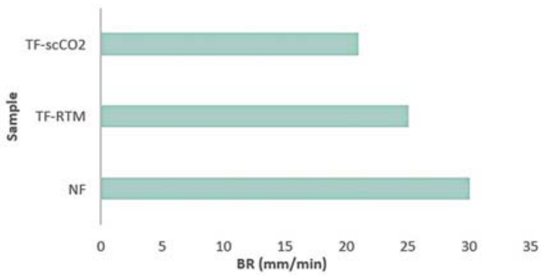

Figure 7. Average BR values of the samples

The average onset temperature and char yield of the samples burned in RTM and $scCO_2$ chamber are tabulated in Table 3. When compared to NF, the flame retardants decreased the textile's onset point, that is, weight loss in treated samples began earlier than that of NF. On the other hand, treatment process provides higher char yield values compared to that of NF. The higher char residues for treated samples may be ascribed to lower mass loss in BR and LOI tests.

Table 3. Data acquired from thermal analysis

Sample code	Onset of degradation (ºC)	Average char residue at 700 ºC (%)
NF	312.4	24.7
TF-RTM	299.7	32.1
TF-$scCO_2$	278.3	40.2

A textile that is combustible has a LOI value of less than 21%, while a textile that is flame-retardant has a LOI value of 26% or more [29,35]. Referring to this information, all samples performed FR feature as seen in Figure 8. The average LOI values for NF, TF-RTM and TF-$scCO_2$ were 27%, 29% and 32%, respectively which were in accordance with BR values. Results confirm that chemical treatment of the NF using two different methods yields improvement in FR feature of the seat upholstery. TF-$scCO_2$ performed the best result both in BR and LOI tests showing that, apart from its other advantages, $scCO_2$ can also be good candidate in terms of enhancing FR performance of the fabrics. One of the reason for improving FR is the characteristics of ZnO metallic nanoparticles which may have acted as heat sink during the BR and LOI tests. Heat release rate was augmented due to good thermal conductivity of the ZnO nanoparticles leading to flame retardancy. The other reason for improving FR can be attributed to the decomposition of $Al(OH_3)$ at about 180 ºC and giving off water so as to act as an extinguisher. In $scCO_2$ reactor, the sample fabrics were wrapped with the $scCO_2$ layer protecting the fibers being destroyed by the flame. Furthermore, TF-$scCO_2$ samples may function better due to their capacity to break down into additional gas products from the nitrogen atom. The higher FR performance of $scCO_2$ than that of RTM method may be attributed to the physical conditions of the RTM. In RTM, the fabric was impregnated by the chemical treatment mixture which was pumped and physically compressed onto the fabric sample leading to lower impregnation compared to that of $scCO_2$ method.

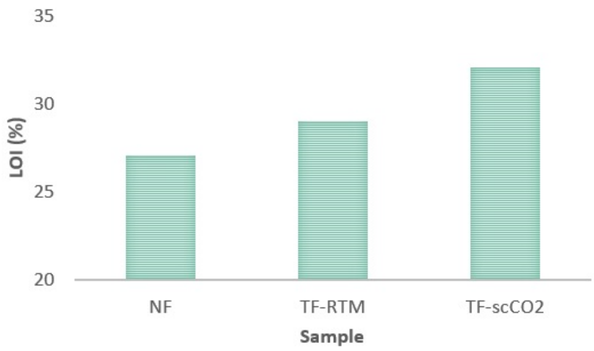

Figure 8. Average LOI vs. samples

4. CONCLUSIONS

Automotive seat upholstery fabric samples were successfully treated with various chemicals to improve FR performance. Aforementioned concentrations of related chemicals provided considerable enhancement for both treated samples referring to BR and LOI tests. Two different impregnation methods of RTM and $scCO_2$ were utilized to carry out chemical treatment to fabric samples. The results showed that treated fabric in $scCO_2$ depicted the best LOI performance of 40%, char yield of 40.2% and BR of 21 mm/min among NF and TF-RTM. On the other hand, RTM also demonstrated better FR performance than that of NF. However, impregnation in $scCO_2$ was more influential on enhancement of FR performance than that of RTM due to limitation of RTM method’s physical conditions. Thus, it can be said that methods and chemical treatment used in this study gave promising results for variety of applications in FR automotive technical textiles.

5. ACKNOWLEDGEMENT

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