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Cold Plasma Treatment in Wet Chemical Textile Processing

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Abstract
Nowadays, cold plasma technology is highly involved in textile processing either to assist conventional wet-chemical processing and/or create innovative products. Plasma surface treatment is an ergonomically simple process, but the plasma process and its effect on the fibre surface are more complex due to the interplay of many concurrent processes at a time. The efficiency of plasma treatment mainly depends on the nature of textile material and the treatment operating parameters. The main objective of this review paper is to summarise and discuss the application of plasma treatment and its effect on the pre-treatment, dyeing, printing and finishing of natural and synthetic textile fibres. However, the application of plasma technology to different types of textile substrates has not been fully addressed.

Key words: *cold plasma, textile, fibre, surface modification, wet-chemical processing.*

Introduction

Textile surface preparation and the modification process can be done by conventional and/or advanced innovative methods. Surface preparation methods, including singeing, desizing, scouring, bleaching and mercerising, are primarily used for the removal of impurities like sizing residue, waxes and fats, colouring materials, hemicellulose in cotton, etc., to enhance the hydrophilic behaviour, affinity for pigments and dyestuffs, uniformity and surface tension of fibres. On the other hand, surface modification methods including vapour deposition, wet chemical processing and plasma treatment have been used to increase or decrease wettability as well as improve the adhesion, antistatic and other properties of textile surfaces by incorporating different polar groups [1, 2]. From these techniques of textile surface preparation and modification, plasma treatment has an advantage over conventional chemical pretreatment and finishing processes, since it is carried out without the use of water and chemicals, which are highly toxic to the environment. This enables cost savings and environmentally friendly processes. So far, it has only modified the outermost surface characteristics of the textile substrate without changing its bulk properties [3, 4].

Plasma is a state of matter which has a high number of molecules and/or atoms either thermally, electrically or magnetically ionised or charged. Its excited gas state consists of photons, positive and negatively charged ions, metastabilisers, radicals, atoms, molecules and electrons. A so-called quasi-neutral state is formed. Based on the temperature of electrons, ions and neutrals, plasma can be classified into thermal (hot) and non-thermal (low-temperature or cold) plasma. In thermal plasma, all the species (i.e. electrons, ions and neutrals are at a similar temperature) composing it are in thermodynamic equilibrium. The temperature of the plasma species produces a high volume of heat (>1,500 °C) and is used as a source thereof. It is only used for changing the bulk material properties, being not suitable for textile and nearly all other materials. Cold plasma, on the other hand, is maintained at around ambient temperature, or somewhat greater than it (20-250 °C). This is as a result of the electron temperature being much higher than the ion and neutral temperature. It can be successfully applied to textile processing because textile materials are generally more heat sensitive polymers than metals and ceramics [4-7].

Cold plasma can be made in a vacuum under low pressure or at atmospheric pressure, both of which are used for textile surface modification. As mentioned above, cold plasma contains many reactive species, and these can initiate physical and chemical reactions on the surface of textile substrates. Such modifications are limited to a few nanometers in depth, which only changes the outermost chemical, structural and surface properties of a substrate. Thus, plasma treatment can impart a desired property to textile fibres. The effectiveness of surface modification depends on plasma conditions such as the type of gas/monomer, the flow rate, pressure, power, treatment time and types of materials treated. Plasma treatment is very suitable, versatile and multifunctional in the textile process [8, 9].

Within the last seven decades, plasma technology has been more studied to improve the wettability, dyeability, printability as well as the electrical, hydrophilic, hydrophobic, antimicrobial and adhesion properties of both man-made and natural fibres [10-13]. In addition, surface modification by cold plasma can be applied in many different textile areas.

In literature, a number of reviews have been written on the cold plasma treatment of textiles. Some of the review

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articles are more specific like atmospheric pressure or low pressure plasma [14-19], whereas others are more general overviews of plasma treatment and their effects on textile surfaces [20-22]. In general, the result of plasma surface modification is either of a hydrophilic or hydrophobic nature on the surface of the fibre. In this paper, more priority is given to the contribution of hydrophilic plasma treatment to the effectiveness of each textile processing either in parallel with conventional wet chemical processing or alone, because the hydrophilic property of textile material plays a vital role in textile pre-treatment and finishing processes. Irrespective of the types of textile fibre and processing technology, wetting is the prerequisite for all wet-chemical processes viz. pre-treatment, dyeing, printing as well as finishing stages. In addition, it improves the quality of the end product.

Mechanism of plasma–textile surface interaction

Before discussing the contribution of hydrophilic plasma in textile processing, it is very important to understand the interaction mechanism between plasma species and textile materials. The effect of plasma treatment on the material surface mainly depends on the types of interaction between the plasma species and textile fibres. When the excited plasma species, viz. ions, electrons, meta-stables, and neutrals are bombarded on the textile surface along with energetic ultraviolet photons, they can break chemical bonds and initiate various reactions on the surface. Generally, plasma can give two kinds of surface modification. The first involves chain scissions on the surface (i.e. etching, cleaning or activation) and cross-linking through the reactions of inter- and intra-molecular polymer chains together. These are produced by inert gases (argon & helium), as well as by reactive atoms and molecules (hydrogen, oxygen, nitrogen and ammonia). The second type involves plasma-activated surface reactions like polymerisation and grafting, formed using various polymerising gases and monomers [15, 23].

Contribution of plasma technology to wet-chemical textile processing

This section discusses a number of academic research efforts with regard to textile pretreatment, colouring and finishing using plasma technology. A number of plasma processes and their effects are presented, which are neither complete nor exhaustive, with only examples that demonstrate the possible applications of cold plasma technology to textile processing being presented.

Application of plasma in the pretreatment of textiles

The pre-treatment of textile materials is the primary process conducted in textile wet chemical processing, the objective of which is to remove different kinds of impurities, such as sizing agents in warp yarns and oil residues that are added or stained by the machine during the fabric manufacturing process. Pre-treated textile substrates have a higher water absorption capacity and contribute significantly to the improvement of the subsequent dyeing (dyeing or printing) and finishing processes carried out to achieve the desired properties and end uses of the textile fabric [24].

Generally speaking, wet-chemical pretreatment processes require prolonged treatment time, large amounts of chemicals, and high treatment temperature, resulting in low production efficiency, high energy consumption and heavy loading of effluent to the environment. Plasma treatment has had a great effect on the textile industry, and its etching effect could be used for surface cleaning. As a result, it is possible to use plasma treatment as a single process as an alternative to the conventional chemical-based pretreatment process. Meanwhile, plasma is used to pretreat the textile material first, followed by mild chemical pretreatment. This has the effect of reducing the treatment time, shortening the processing time, reducing the amount of chemical used, and lowering the treatment temperature. It also gives a higher production rate and lower effluent load, and an energy-saving pre-treatment process can be achieved. For example, Persin et al. [25] studied the sorption characteristics and surface properties of modal, viscose and lyocell regenerated cellulosic fabrics by using conventional wet-chemical pretreatment and low-pressure-oxygen plasma treatment, separately. In fact, both treatments modified the surface chemistry of cellulose fabrics. However, the content of carboxlic acid was increased ~ 4.8% by the wet-chemical pre-treatment, whereas plasma treatment increased it by ~ 9.7%. The authors concluded that oxygen plasma treatment has a significant effect on the surface energy as well as on the polarity of cellulosic fabrics. In another study, Liu and Lu [26] applied nitrogen glow-discharge plasma on Polyacrylonitrile (PAN) fibres to investigate its surface energy and wettability using contact angle measurement. The results revealed that the plasma treatment reduced the water contact angle on the fibre surfaces. The polarity was increased considerably from 14.6 to 58.7 mN/m, whereas the dispersion component of the surface energy was altered slightly, and the total surface energy rose to 139%. The authors concluded that the increase in surface energy was primarily the formation of hydrophilic groups on the fibre surfaces. Therefore, it is possible to use plasma treatment as a green technology in the pretreatment of textile materials [3, 27].

Improving the efficiency of desizing

The desizing and surface cleaning of textile substrates can be done by applying plasma treatment. However, choosing plasma for the material to be detached from the fibre surface is required, since the fibre structure should not be affected. The desizing of natural, regenerated and synthetic textile materials through plasma technology is a new approach in the textile industry. So far, plasma treatment has replaced conventional wet-chemical treatment to overcome the environmental problems of desizing and reduce effluent treatment costs in the textile industy.

The desizing of cotton and polyester-cotton by plasma treatment was first studied as early as 1973 [28]. Peng et al. [29] also investigated the influence of absorbed moisture on the desizing of polyvinyl alcohol (PVA) on cotton with atmospheric pressure plasma jet (APPJ) treatment by using a mixed gas of 1% oxygen and 99% helium. They reported that the cotton fabric with the lowest moisture regain (MR 1.8%) gave the highest size removal compared to the other fabric treated with MR of 7.3 and 28.4%, respectively. In fact, the percent desizing ratio (PDR) reached 96% after 64 s exposure time, followed by 20 min hot washing, after which the fabric was shown to be as clean as the control sample through SEM analysis. Cai et al. [30] studied the effect of air/He and air/O_2/He atmospheric plasma treatment to desize PVA on cotton fabric. It was shown that air/O_2/He plasma might have a greater effect on PVA size removal than air/He plasma treatment. In addition, it was found that both plasma treatments served to remove some PVA size material directly and also significantly facilitated PVA removal by subsequent washing. Indeed, X-ray photoelectron spectroscopy (XPS) displayed that plasma bombardment broke down molecular chains into a smaller size. The authors concluded that this effect facilitates the swelling, dissolving, and dispersing of PVA. In another work, Cai and Qui [31] reported on the mechanism of air/oxygen/helium atmospheric plasma action in desizing PVA on cotton fabric as compared to conventional H_2O_2 desizing. The result revealed that plasma-aided desizing of PVA is more effective than the conventional desizing process. Li et al. [32] investigated the influence of He/O_2 APPJ treatment on subsequent desizing of polyacrylate on PET fabrics in the wet process. They found that oxygen-based functional groups enhanced plasma-treated polyacrylate sized fabrics. Sequentially, 65 s plasma treatment and 5 min $NaHCO_3$ desizing achieved more than 99% PDR. When compared to the conventional wet-process, the plasma treatment significantly reduced the desizing time. In another paper, Li and Qiu [33] studied the influence of He/O_2 APPJ and ultrasound treatment on the desizing of blended sizes of starch phosphate and PVA on cotton fabrics. They found that the fibre surfaces are nearly as clean as unsized fibre surfaces after 35 s plasma treatment followed by ultrasound desizing for 20 min at 60 °C. The authors concluded that the desizing of the blended sizes by APPJ and ultrasound together gives a good result and provides a new approach to decrease the consumption of water, energy and chemicals.

Kan and Yuen [34] compared the performance of oxygen APPJ plasma treatment in the desizing of grey cotton denim fabric followed by the enzymatic colour fading process with conventional enzyme desizing treatment. The authors reported that the plasma treatment followed by the enzymatic fading process showed a remarkable colour fading effect on grey cotton denim fabric. Bae et al. [35] studied the size removal of PVA, polyacrylic acid esters (PAA) and their mixture on PET fabric using low pressure oxygen plasma treatment. They found that the removal of PVA was higher than that of PAA, while the removal of their mixture was moderate. Li and Qiu [36] investigated the comparative advantages of He/O_2 APPJ plasma-aided size removal with the conventional desizing of polyacrylate on PET fabrics. It was found that the plasma treatment greatly reduced the desizing time. In fact, SEM analysis showed that after 35 s of plasma treatment, the PET fibre surfaces were as clean as unsized fibres after $NaHCO_3$ desizing. XPS analysis also revealed that a number of oxygen-containing functional groups increased for the plasma-treated polyacrylate sized PET fabrics. Cai et al. [37] reported that air/He and air/O_2/He atmospheric-pressure plasma treatments removed some of the PVA on rayon (viscose) fabric and found that plasma treatment followed by one cold wash and one hot wash was as effective as the conventional desizing process followed by two cycles of cold and hot washing. Indeed, a PDR of 93.36% was achieved by the air/O_2/He plasma-treated sample after 5 min and cold washing alone. As elaborated above, the authors concluded that the application of plasma technology in the desizing of PVA, PAA and other sizing agents provides an alternative approach to decrease the consumption of energy, water and chemicals involved in conventional desizing processes.

Enhancing the effectiveness of scouring

Scouring is carried out to remove impurities, especially wax, oil, grease and dirt of grey textiles, in order to produce a clean background and improve the water-absorbing property, which is necessary for subsequent dyeing and printing processes in conventional wet chemical and/or plasma processing.

Szabó et al. [38] conducted atmospheric air plasma treatment of raw linen fabric using a diffuse coplanar surface barrier discharge (DCSBD) plasma reactor to evaluate the physical and chemical properties of the fibre surface. The authors found a significant difference between the plasma treated and untreated linen fabric properties, such as the improvement of wettability, surface energy, wickability and the O/C ratio. In addition, the topography of the surface created by plasma treatment was almost unchanged, and the etched waxy did not recover within 14 days aging at standard conditions. Kan et al. [10] investigated the efficiency of atmospheric pressure He & O_2 plasma treatment of grey cotton fabric through conventional desizing, scouring and bleaching processes in order to compare it with the efficiency of conventional wet treatment. The outcomes obtained from wicking and water drop tests revealed that the wettability of grey cotton fabrics was more improved after plasma and yielded better results than conventional desizing and scouring. In another paper, Sun and Stylios [39] studied the effect of low pressure O_2 plasma treatment on the scouring of wool and cotton fabrics and found that wool and cotton fabric specimens exhibited a high hydrophilicity and better scouring processing rate by nearly 50% after the treatment. The experimental results revealed that exposing grey wool and cotton fabrics to O_2 plasma changes the oil, fat and wax content; for example 8.86% and 7.12% of these impurities were removed after O_2 plasma treatment for wool and cotton fabrics, respectively. Kan and Lam [40] reported that APPJ He & O_2 plasma treatment effectively removed the impurities from 100% grey cotton knitted fabrics and significantly improved the water absorption property. Comparably, by performing the procedure first with the plasma and scouring process afterwards, the total treatment time is reduced. The decrease in carbon content, as shown in XPS, revealed that the removal of surface impurities and increasing oxygen-to-carbon (O/C) ratios of the plasma treated knitted fabrics coincided with the enhancement of hydrophilicity.

Wang et al. [41] investigated the effectiveness of Dielectric Barrier Discharge (DBD) for air plasma, and oxygen plasma in a vacuum system was used successfully as the pretreatment prior to cotton bioscouring, aiming to increase the accessibility of pectinases to the pectic substances on the cotton fibre. The authors concluded that both plasma treatments could enhance cotton bioscouring. Canal et al. [42] studied the scouring of knitted Merino wool fabric using water vapour plasma gas in a vacuum chamber, followed by Soxhlet extraction with CH_2Cl_2 and an aqueous solution of nonionic surfactant. Regardless of the scouring process carried out on the fibres, water vapour low temperature plasma (LTP) treatments significantly reduced the contact angle from 112° or 103° to around 54°. All papers involving scouring found that LTP treatment played a great role in scouring processes and provided an environmental friendly approach to the textile scouring process.

Application of plasma treatment in the dyeing of textiles

The application of plasma as a pretreatment in textile wet chemical processing increases the surface energy and improves the hydrophilic behaviour of textile materials. These changes in surface energy are primarily due to the introduction of polar groups on the surfaces of textile substrates during plasma treatment or through post plasma interactions. The consequences of enhanced wettability and capillarity, the creation of reactive sites on fibre surfaces, the enhancement of the surface area, and other actions may be an improvement in the dyeing properties of textile materials, depending on the plasma operating conditions. The improvement of the dyeing properties of textiles has many benefits, as follows: (i) an increase in the dyeing rate, (ii) increased dye-bath exhaustion, and (iii) improved dyeing homogeneity. Morent et al. [20] and Jelil [21] reviewed some previous research papers related to the application of plasma treatment in the dyeing of textiles. All these research papers reported that all types of fibres treated by plasma improved the dyeability of the textile substrate.

Demir [43] reported on the air/Ar atmospheric plasma treatment of mohair fibres to examine its hydrophilicity, fibre to fibre friction, grease content, dyeing, shrinkage and colour fastness properties. The results indicated that the hydrophilicity, fibre friction coefficient, dyeability and shrinkage properties of the mohair fibres were enhanced after plasma treatment. A similar work was also reported by Atav and Yurdakul [44]. Yaman et al. [12] reported that vat-dyed polypropylene (PP) fabrics showed a significant increase in colour strength when they were pretreated with atmospheric pressure of argon or air plasma treatment. Sun and Stylios [39] also reported that low-pressure oxygen plasma treatment significantly increased the dyeing rate of wool and cotton fabrics. This process led to faster and higher exhaustion of dyestuffs to the fabric. Moreover, this positive effect could lead to shorter dyeing times and a reduction in discharging effluents to the environment. Carneiro et al. [45] presented corona-treated and untreated dyed cotton fabric with direct dyes in which the same dyeing procedure of the time–temperature profile for both substrates (40 °C for 1 h) was used without any auxiliaries except sodium sulphate (2 g/l). The exhaustion levels are very similar for all samples other than raw and untreated fabric, which shows a much lower exhaustion level. In addition, corona-treated dyed samples are darker in colour than the untreated samples, with the deviations in chroma and hue probably being due to differences in the initial undyed fabric. The authors concluded that the corona treatment offers a major advantage over classical methods by eliminating pre-washing; scouring–bleaching; steaming; intermediate drying, and post-washing in the dyeing process. In another paper, Labay et al. [46] reported that within 60 s the initial dyeing rate revealed an increase of 58.3% due to the effect of air corona plasma on the acrylic fibre surface under isothermal conditions at 30 °C. At the end of the dyeing process, the plasma-treated fabrics absorb 24.7% more cationic dye (CI Basic Blue 3), and the K/S value of the fabric increases by 8.8%. Oliveira et al. [47] studied the dyeability of polyamide 6,6 (PA66) fibres after DBD air-plasma treatment and found that plasma treatment allows a high level of direct dye diffusion and fixation in PA66 fibres at lower temperatures and shorter dyeing times than conventional dyeing processes. This is due to the formation of low-molecular acidic molecules that behave as a dye “carrier” and, by making micro-channels on the PA66 surface, seem to initiate better dye diffusion into the fibre cores. Boonla and Saikrasun [48] investigated the adsorption kinetics of lac dyeing on silk fibre surfaces using oxygen and argon plasma treatments. The authors found that the adsorption reached equilibrium at 60 min of the dyeing time. The adsorption capacity for the plasma-treated silks was improved compared to that of the untreated sample. Moreover, argon-treated silk adsorbed more than oxygen-treated silk fibres. Another work concentrated on silk fabric using DBD plasma treatment before dyeing with yerba mate natural dye [49]. Similar experiments on proteins fibres viz. wool and silk with air plasma treatment to increase the dye affinity of fibres were also reported by Inbakumar and Kaliani [50]. Öktem et al. [51] investigated the dyeabilities of PET and polyacrylamide (PAm) fabrics with basic dye using i*n situ* polymerisation of acrylic acid, water, air, argon and O_2 plasma treatment in a glow-discharge reactor. The authors confirmed that the surface dyeablilities (K/S values) of both plasma treated PET and PAm fabrics were significantly improved. In another study, Öktem et al. [52] also reported on the treatment of polyester/cotton fabrics with acrylic and water plasma, where the treated fabrics showed a much higher dyeability than the untreated polyester/cotton fabrics. Nasadil and Benešovský [53] tested the dyeability of woven cotton fabrics after plasma surface modification (400 W, exposition time 5 s). The results indicated that the plasma-treated samples showed a deeper shade of colour than the untreated samples.

Other possible explanations for the positive influence of plasma treatment on the dyeing of wool [54-56], nylon [57], cotton [58], PET [59-62], silk [63], PP [64,65] and linen [66] fibres were also reported. Generally, the dyeing of desized, scoured, and plasma-treated fabrics was carried out using reactive dye, direct dye, and natural dyes. In addition, dye absorption also depends on the type of fibre used. A previous study showed that plasma played a significant role in altering the surface composition of the fibre. Thus, the changes in surface composition are likely to affect the dyeing behaviour of a dyeing system. Therefore, the dyeing properties were improved due to the surface modification of fibres either chemically, physically or both.

Application of plasma treatment in the printing of textiles

This section reviews and discusses the application of plasma treatment and its effect on the printing of natural and synthetic fibres. Nowadays, cold plasma offers an attractive pre-treatment approach to the pigment inkjet printing of textiles. Hence, plasma treatment can improve the application of paste coating on textile fabric before digital ink-jet printing. Thus, most papers published have focused on digital ink-jet printing.

Kan et al. [10] applied APP treatment as a pretreatment to enhance the deposition of printing paste to improve the final colour properties of digital ink-jet printed cotton fabrics. Experimental results showed that plasma pretreatment could significantly increase the colour yield even after washing. In addition, colour fastness to crocking and laundering were also enhanced when compared to the control cotton fabric printed without plasma. Similarly, Yuen and Kan [67] also reported the effect of LTP treatment on enhancing the performance of pretreatment paste containing sodium alginate so as to improve the properties of ink-jet-printed cotton fabric. The results revealed that the dye uptake and colour fastness properties were increased due to plasma treatment.

A similar experimemt on cotton fabric was reported by Kan [68].

Chvalinova and Wiener [65] used a DC-SBD type of atmospheric discharge that provides a homogeneous effect over a very short distance, as compared with standard volume DBD, at atmospheric pressure to improve the acid dye sorption of wool fabrics. Experiments confirmed that the erosion of the surface layer of cuticle by plasma treatment adsorbs more dye intensively on wool fabric at lower temperature. Radetić et al. [69] also reported on the application of radio-frequency capacitively coupled plasma treatment on wool fabric. The outcomes showed that plasma treatment improved wool hydrophilicity, leading to a significant increase in the colour yield of wool prints. In another study, [70] Maamoun and Ghalab presented that the pretreatment of a wool/polyester (45/55) blended substrate with air plasma can enhance the K/S values of printed samples, using acid milling dye and reactive vinyl sulphone dye mixtures and incorporating only urea in the printing pastes at pH 7, at a discharge current of 2.5 mA and for a treatment time of 3 min. The authors concluded that, in future, plasma treatment of wool can replace the wet pretreatment processes for wool printing. In addition, different research papers have been published regarding the application of plasma treatment in the printing of polyester [71-78], silk [79] and PP [80, 81] textile substrates.

Application of plasma treatment in the finishing of textiles

Many properties of textiles are more related to the outer surface rather than to the bulk, and hence plasma processing is an attractive alternative to conventional processes [82]. The effect of plasma treatment has to optimise the interaction between the fibre surface and the finishing product that is added to the bath. The treatment effects are achieved by bringing about surface modifications on a micro- or nano-scale without changing the bulk properties of the textiles. The effect can be advantageous in two ways: (i) by improving wetting properties of the textile product, and (ii) by enhancing the interaction between the finishing product and fibre surface, i.e. less of the finishing product is needed. The properties of a plasma-treated and finished textile can also be enhanced, as compared to a textile merely finished by the classical method to which the same amount of the finishing product is added [20].

Plasma treatment with different kinds of plasma gases and/or monomers can impart unique functionalities to textile substrates. A lot of research has been done on this and reported in the literature. Shahidi and Ghoranneviss [83] reported that low-pressure oxygen plasma treatment completely sterilised cotton fabrics inoculated with various concentrations of staphylococcus aureus. This finding was explained by the fact that highly energetic UV light and activated free radicals generated during plasma treatment weakened the cell wall of the microorganisms by reacting with the hydrocarbon bonds, causing the disruption of unsaturated bonds, particularly the purine and pyrimidine components of the nucleoproteins. The authors suggested that oxygen plasma can be effectively used as an alternative method for sterilising and protecting cotton fabrics. Vesna et al. [84] also studied corona treatment for fibre surface activation that can facilitate the loading of Ag nanoparticles from colloids onto polyester and polyamide fabrics and thus enhance their antifungal activity against candida albicans. Polyester and polyamide fabrics pretreated by corona treatment loaded with Ag nanoparticles showed better antifungal properties compared to untreated fabrics. In addition to sterilisation, plasma treatments can also impart antimicrobial and antibacterial functionality or aid in antimicrobial finishing [85-91].

Cold plasma treatment can be used as an effective method for modifying the surface properties of wool fibre by overcoming the drawbacks of the conventional wet-process. Plasma treatment could impart significant shrink-resistance and anti-felting properties to wool fabric. The shrink proofing of wool fabric by plasma, both at atmospheric pressure [43, 92, 93] and at vacuum pressure [94-97], was initiated to replace the classical wet-processes that cause various degrees of environmental stress.

The resistivity of textile material can be reduced by introducing functional groups at the fibre surface through plasma treatment and by forming hydrogen bonds with atmospheric water. Kan and Yuen [98] studied the relationship between the moisture content and half-life decay time for the static properties of PET fabric. The results showed that an increment in moisture content would result in shortening the time for the dissipation of static charges. Moreover, there was a great improvement in the anti-static property of oxygen plasma-treated polyester fabric after compared with that of polyester fabric treated with a commercial anti-static finishing agent. Rashidi et al. [99] also investigated the effect of low pressure air plasma on the surface resistivity of cotton and PET fabrics. The surface resistivity of cotton and PET is dramatically reduced after plasma treatment. Similar research works related to surface resistivity have been published by different authors [26, 100, 101].

In general, due to the wide application of plasma treatment in the finishing of textiles, a review of all the different plasma processes and their finishing effects could not be incorporated in this paper. However, there is a number of excellent review papers that included the impart of unique functionalities to textile materials such as wrinkle resistance, the self-cleaning function, UV protection, flame retardancy, etc. by applying plasma treatment in textile finishing [20, 21, 102].

Development of plasma technology in textile

Even though the plasma idea has been around since the 1920s, the earliest textile plasma treatments started in the 1960s and focused on the enhancement of wettability and shrinking resistance [103]. More recently, in the 1980s many laboratories across the globe performed vacuum plasma treatments on a variety of textile materials, with significantly promising outcomes [3, 104, 105]. The vacuum plasma system can be generated by alternative current (AC), direct current (DC), radio frequency (RF) or microwave frequency (MW), usually between 0.1 and 100 Pa [106]. However, it is restricted to the batch process i.e. the size of the reactor determines the size of textile substrates to be treated. This limitation led to the development of atmospheric pressure plasma treatment in the open air [107]. In atmospheric pressure plasma there are four main kinds of plasma systems which are used for textile applications, viz. dielectric barrier discharge (DBD), corona discharge, atmospheric-pressure glow discharge (APGD) and atmospheric-pressure plasma jet (APPJ) [9]. Until now, however, there has been no confirmed evidence that shows the superiority of atmospheric pressure plasma over low-pressure plasma for textile applications. Plasma reactor technologies/devices, plasma sources, plasma application and usefulness of plasma process at industrial levels, as a result of higher power or energy densities and the production of active species, are described by J. Reece Roth [108]. Russian scientists were the pioneers in developing a roll-to-roll vacuum system in the fabric width on an industrial scale for space missions [106].

In recent years, textile companies have already started to use plasma technologies to impart new functionalities to textile materials in different countries. Some of these companies are as follows: (i) The Pavlovo Posad Shawl manufactory (Moscow, Russia) applied plasma treatment to impart anti-felting and shrinking resistance to woollen fabric before printing [109]; (ii) Avondale mills (Georgia, North America) used plasma technology to treat cotton and cotton/polyester fabrics to give stain and water repellency; (iii) the Richter international company (Canada) introduced plasma treated wool socks into the market with the name of "plasmawool"; and (iv) the textile finishing company Textilveredelungs GmbH Grabher (Lustenau, Austria) developed hydrophobic and hydrophilic functionalities in textiles with low pressure plasma treatment [110]. Moreover, Angora cottage industry (Kulu, India) successfully established atmospheric plasma for spinning 100% Angora yarn and producing new products [111].

Nowadays, due to the success of plasma technology in textile industries, a number of plasma technology suppliers have made a significant contribution to developing plasma machineries and processes designed for introducing a wide range of functionalities on a textile substrate to satisfy customer demand at the industrial level. Some of these supplier companies are Europlasma (Belgium), Textilveredelungs GmbH Grabher (Austria), P_2i (UK), HTP Unitex and Mascioni (Italy), which provide standard and custom-designed low-pressure plasma machines for batch treatment, whereas Dow Corning Plasma Solutions (Ireland), Arioli (Italy), Softal and Ahlbrandt (Germany), AcXys (France), InspirOn Engineering Pvt. Ltd. (India), Tri-Star and APJeT (USA) offer atomosphric pressure plasma systems for inline continuous treatment [3, 105]. Plasmas have the crucial advantage of reducing the usage of chemicals, water and energy. Moreover, they offer the possibility to obtain typical textile finishes without changing the key textile properties. No wonder there is an increasing interest in plasma for textile materials processing. This overview consists of four parts: introduction to plasma; plasma interactions with textile materials and potential applications; evaluation of the current level of industrialisation; and conclusions. Despite ongoing efforts to integrate plasma treatments in the textile world, important hurdles for industrialisation still exist. Key issues are surface cleanliness, the three-dimensional structure and the large surface area (because of the individual fibres). Although specific textile properties (i.e. chemical composition, surface cleanliness, three-dimensional structure, a large surface area, and affinity for moisture and air), textile-sector-related issues and plasma technology itself are considered a challenge, further research has been going on in full to overcome these constraints, using the technology in the textile industry in various application and at the mass production level.

Conclusions

The aim of this review was to offer relevant information gathered from academic research papers and books to the reader and assist them in understanding the different plasma processes and their effects in textile wet chemical processing. However, it is often difficult to review an objective scientific or industrial comparison of plasma processes and their effects. This may be the main reason why the development of plasma technology on an industrial scale has not yet taken place in the textile industry to the extent expected. Moreover, plasma–surface interactions are highly complex due to the interplay of a variety of concurrent processes at a time. This complexity includes many factors, such as the chemistry of plasma gases, the nature of the substrate, and the treatment operating parameters. Plasma treatment has been demonstrated in laboratory and industrial prototypes for textiles. Cold plasma technology offers a new approach to introducing the required functionalities to textile materials that produce a unique product. In fact, the release of toxic chemicals can be eliminated through plasma treatment, and it is considered as a green process that is viable to replace the classical wet chemical process. In addition, plasma treatment can selectively enhance the surface properties of textiles within short treatment times without changing bulk properties, as compared to the conventional methods. Moreover, plasma can create innovative surface characteristics that are not formed by traditional wet chemical processing. In general, the application of plasma as a pre-treatment in textile wet chemical processing increases the surface energy and improves the hydrophilic behaviour of textile materials. Consequently, the dyeing and finishing properties of textile materials can be improved. Due to this potential, plasma treatment has already been comprehensively investigated on a laboratory scale. It is also integrated into the textile industry, even if only to a limited extent.

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