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A Brief Review on Plasma Treatment of Textile Materials

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Abstract

The textile industry is searching for innovative production techniques to improve the product quality, as well as society requires new finishing techniques working in environmental respect. These techniques show distinct advantages, owing to their ability to modify the surface properties of inert materials, sometimes with environment friendly devices. Surface modification of textile fibre by atmospheric plasma treatment imparts certain desired properties in terms of wettability, adhesion promotion, surface energy to the fibre to have a pre-barrier effect which will not only allow the adhesion of the particle loaded liquids on the fibre surface but will also retain very good air permeability. This article delineates a review on plasma treatment imparted to the textile fibres of both natural and synthetic origin to be applied in the field of textiles along with a comparative analysis of such treatment with the conventional method of surface modification of the textile fibres.

Keywords: Plasma treatment; Surface modification; Surface energy; Textile materials

Abbreviations

AC: Alternate Current; APGD: Atmospheric Pressure Glow Discharge; APPJ: Atmospheric Pressure Plasma Jet; BOD: Biological Oxygen Demand; COD: Chemical Oxygen Demand; DBD: Dielectric Barrier Discharge; DC: Direct Current; LTE: Local Thermal Equilibrium; MW: Micro-Wave; PP: Poly Propylene; PSM: Plasma-Surface Modification; RF: Radio Frequency; SED: Specific Energy Density; TOC: Total Organic Carbon

Introduction

The textile industry is searching for innovative production techniques to enhance the product quality, as well as society requires new finishing techniques working in environmental respect [1]. Plasma treatment of textiles is a growing function of plasma technology which is achieved *via* surface alteration without modifying the bulk properties of the materials [2]. “Plasma” is derived from the Greek language and refers to “something moulded or fabricated” [3]. Plasma or “Radiant Matter” as it was known, was first identified by Sir William Crook in 1879. Radiant matter was later called “Plasma” by Irving Langmuir [4] in 1928. Using Thierry’s low-pressure systems, plasma treatment of textiles is used to pre-treat fibres to increase wettability which allows for solvent free dyes to absorb and bond very strongly. Also, plasma treatment of textiles is used to coat fabric with a specialized layer with varying characteristics which enable the coated fabric to become hydrophobic, repelling water or other liquids. The protective coatings applied on to the textiles through plasma technology make the textiles more durable [5]. Plasma contains free radicals, electrons and heavy particles which help in surface modification [6]. Once in the gas phase if additional energy is forced into the system, then the gas becomes ionized and reaches the plasma state. When the plasma comes into contact with the material surface it transfers the additional energy from the plasma to allow for subsequent reactions to take place on the material surface [7] and it can be obtained between electrodes in high frequency devices (typically 40 kHz or 13.56 MHz) or with microwave generators (2.45 GHz) [8]. Plasma surface treatment raises the surface energy of many materials so as to improve the bonding characteristics [9]. These treatments show distinct advantages, because they are able to modify the surface properties of inert materials, sometimes with environment friendly devices. Although the surface of textile materials donates little to the total mass of the material, it is often responsible for the many end-use properties of textile products [10]. Recent developments in the plasma treatment of textile materials have revealed its enormous potential as an alternate technology for the textile processing, due to its cost saving, water saving and eco friendliness. Wet processing of fabrics, such as scouring, desizing, bleaching, dyeing/ printing, and finishing, consume enormous amounts of water, produce pollution through effluents, and consume large amount of energy. As a result, it has become necessary to look for ‘green processes’. Plasma technology, when used effectively, can offer ‘greener’ possibilities as it is a dry process, it is energy efficient and needs minimum amount of chemicals with no down-stream pollution effect. This technology enhances the increase of micro roughness (anti-pilling finishing of wool) and the production of radicals to obtain hydrophilic surfaces [11]. Plasma polymerisation, that is the deposition of solid polymeric materials with desired properties on textile substrates, is under development. The advantage of such plasma treatments is that the modification turns out to be restricted in the uppermost layers of the substrate, thus not affecting the overall desirable bulk properties [12]. Such treatments on natural fibres like, wool and cotton, and on synthetic polymers helps to improve their wetting properties. Plasma-Surface Modification (PSM) [13] is an effective and economical surface treatment technique for many materials and of growing interests in textile engineering. Plasma treatments are gaining popularity in the textile industry for their numerous advantages over conventional wet processing techniques. Normally in these treatments the fabrics are treated with antimicrobial finishes and plasma which contains fluorocarbon gas. Plasma surface modification technology offers innovative solutions to adhesion and wetting problems in many

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industries. Component preparation using plasma is an important step prior to printing, bonding painting, varnishing and coating processes. Surfaces in contact with the plasma are bombarded by the energetic species and their energy is transferred from the plasma to the solid. These energy transfers are dissipated within the solid by a variety of chemical and physical processes to result in a unique type of surface modification that reacts with surfaces in depths from several hundred angstroms to 10µm without changing the bulk properties of the material [14]. But in spite of such technical advantages, plasma treatment for surface modification of fibres has a major drawback of inability to penetrate deep into the three dimensional porous structure of textile materials as it majorly influences the surface layer of the materials [15].

Different Type of Plasma Treatment Applications in the Field of Textile

Plasma treatment is subdivided into thermal and non-thermal plasmas [16]. Non-thermal plasmas are those in which the thermodynamic equilibrium is not reached even on a local scale between the electrons and the higher mass particles (neutral atoms all molecules, ions and neutral molecules fragments), Thermal plasmas are characterized by an equilibrium, or a near equality, between the three components of the plasma: electrons, ions and neutrals [17]. Non-thermal plasma is also known as cold plasma, are particularly suited for textile surface modification and processing because most textile materials are heat sensitive polymers [18]. Cold plasmas may be divided into atmospheric pressure plasma and vacuum or low pressure plasmas. There are four main types of atmospheric plasma applied to textile where Corona, the oldest plasma technology applied on the modifications on polymer surfaces is the most primitive one. Corona discharge is usually generated at atmospheric pressure of 1 atm by applying sinusoidal pulses at a frequency of tens of kilohertz and a high voltage in the range of 10-15 kV between two electrodes of different shapes and size sand spaced at about 1 mm. The polymer web usually spends a maximum of a few seconds in the discharge and passes the plasma region at a speed of tens to a few hundreds of meters per minute. Energy depositions are usually 0.1 to a few Joules/cm^2. A schematic diagram of a typical corona discharge device used for plasma surface modification is shown in (Figure 1). Dorai and Kushner [19] studied plasma modification of Poly Propylene (PP) using corona discharge technology. The gas composition was $N_2/O_2/H_2O$ = 78.9/20.0/1.1, at 1 atm and initially 300 K. The downstream electrode length used is 12 cm and the polypropylene web speed is maintained at 250 cm/s. producing a gas residence time of 0.05 seconds. The applied voltage is sinusoidal at 9.6 kHz across a 3 mm gap providing 460 voltage pulses per site. The energy deposition is varied in the range of 0-1.5 Joules/cm^2 by changing the applied voltage 0-20 kV. They observed that increasing energy deposition leads to an increased production of alcohol, carbonyl, acid and peroxy radicals on the polypropylene surface while increasing the gas phase production of O_3 and N_xO_y. This treatment may increase the fibre surface area and the surface roughness. However, it is an uneven treatment for textile because it has a weaker ionization being non uniform and only affecting loses fibres and not penetrating deeply into the fabrics [20]. The second technique is the Dielectric Barrier Discharge technology (DBD), where at least one of the electrodes is covered by a dielectric layer that accumulates the transported charge on its surface. The dielectric layer [21] has two functions: it limits the amount of charge transported by a single micro-discharge and distributes the charge over the entire area of the electrode. This can interrupt the sequence of chemical reactions required to produce important spices. In this regard, several gases have been investigated for modifying the surface properties of polypropylene including He, CO_2, N_2, NH_3 and air. Studies by Massines et al. [22] on the role of gas composition in the DBD treatment of polypropylene showed that O_2, even when present in small quantities, can significantly affect the surface chemistry and hence the level of surface transformation. The nature of the discharge also affects the surface properties of the fibres. Under controlled operating conditions, glow discharges can be produced which are often more effective for surface modification of the fibres. Atmospheric Pressure Glow Discharge (APGD) is such a technique where a frequency of few Hz to MHz and a.c. voltage of 1-100 kV are applied between electrodes inserted into a cell comprising a gas, usually Helium or Argon, at atmospheric pressure [23] and is characterised by a relatively long duration, uniformity and low-to-moderate areal power densities avoiding surface heating or damaging.. Massines et al [24] showed that the surface energy of polypropylene fibre increases from 27 to 62 mJ/m^2 when using a glow atmospheric discharge. Atmospheric Pressure Plasma Jet (APPJ) is the latest surface modification technique and is significantly milder than a plasma torch but still highly effective at room temperature. Plasma jet has advantaged over DBD because it can generate uniform reactive gases and can also be applied to the surface of any shaped object [25]. Atmospheric plasma surface treatment with corona treaters issued to improve wettability of polymeric films [26]. Li and Qiu [27] studied the influence of He/O_2APPJ treatment on subsequent wet desizing of polyacrylate on polyester fabrics. A 99 percent of desizing ratio was achieved after 65 seconds of plasma treatment followed by a 5 minute $NaHCO_3$ desizing. Compared to conventional wet desizing, it was observed that plasma treatment significantly reduced the desizing time. As it is evident, that the increase of wettability is one of the first and well-known effects obtained on textiles witch vacuum reactors using O_2-, air-, NH_3- plasma, together with an enhancement of capillarity of wool and cotton fabrics. In fact, the character of the wool surface can be changed from hydrophobic to hydrophilic, obtaining a reduced felting of tops and fabrics by means of simple corona treaters. Another effect that can be easily obtained with a corona treatment is an overall cleaning of surfaces, due to the ion bombardment in the discharge [28].

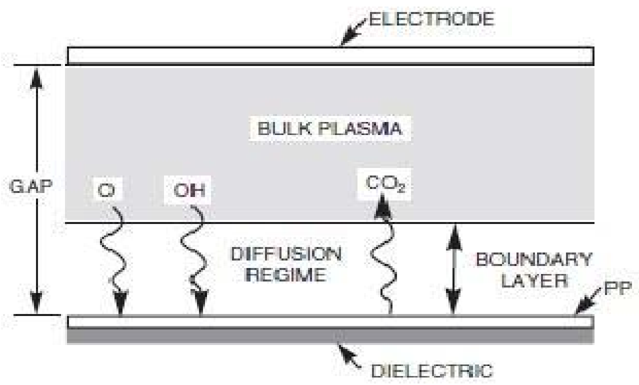

Figure 1: Model for plasma treatment of polymer surface.

Different Schemes Classifying the Cold Plasma Operations

The different parameters based on which the cold plasma operations are classified can be listed as the discharge geometry, electrode arrangement, field configuration, type of plasma generated for example arc, thermal and non-thermal or cold, the excitation frequency like Direct Current (DC), Alternate Current (AC)-driven, Radio Frequency (RF)-driven, Micro-Wave (MW) driven, excitation pattern like the continuous wave, pulsed and the type of gas or combination of gases injected to the discharge area. The schemes of geometry play a very vital role in defining the function of a plasma operation. This is emphasized by Lu, Laroussi and Puech [29] who reported the coaxial geometry of DBD plasma jet which contains a dielectric layer or remains hollow in order to enable working gas injection through the electrode itself. On the other hand, Selwyn et al. [30] introduced the rectangular geometry of APPJ, a capacitive RF discharge, utilizing two bare metal electrodes covered by quartz glass windows from both sides. Another scheme regarding the geometry is the electric field configuration with respect to the gas flow direction. Law and Anghel [31] reported that plasma jets can be divided into linear-field jets, cross-field jets and end-field jets. In the linear field two parallel circular electrodes are arranged around a dielectric tube to generate an electric field parallel to the feed gas flux while in the cross-field arrangement a coaxial electrode alignment is applied to create an electric field perpendicular to the gas flux. When only one electrode is used and positioned at one end in the dielectric tube, where the gas is introduced, the arrangement is known as end-field jet. Excitation frequency and Specific Energy Density (SED) schemes determine the plasma properties such as the temperatures and densities of the active species. DC and AC plasma jets usually generate Local Thermal Equilibrium (LTE) plasmas with high gas temperatures. Plasma coagulators for surgery applications operate at radio frequencies measured in MHz range. DC plasma jets in air or noble gases like He or Ar can also be operated in self-pulsing mode. Transient spark discharges [32-34] generate plasma properties which are obtained with rectangular high voltage or sinusoidal driven plasma jets in the kHz range. RF jets usually operate in the frequency range of 1-100 MHz, where ions are not able to follow the electric field as easily as the lighter electrons [35]. MW plasmas are generated and sustained by electromagnetic radiation in the microwave frequency range 300 MHz- 300 GHz. The different plasma operations can also be classified by SED scheme which is obtained by dividing the power dissipated into the plasma by the gas flow rate when treated with barrier or corona discharges [36]. Non-LTE plasma jets do not exceed a SED of about 102JL-1.Typical translational plasmas like gliding arcs, spark jets or RF plasma jets show a SED in the range of 102 to 103JL-1. However, this discussion on the several schemes shows that plasma jets can be generated in a wide range of properties and a proper characterization of plasma must include the determination of all the above mentioned parameters.

Comparison of Conventional Method and Plasma Treatment on Fibre Surface

Pre-treatment and finishing of textile fabrics by plasma technologies increasingly begun to start to replace conventional wet chemical application not only because of economic consideration but also for ecological considerations. The water requirement of the plasma treatment is relatively small, and about 50 percent of the water pollution is due to high Biological Oxygen Demand (BOD) wastewater from desizing. Auxiliary chemicals which are used in the bleaching bath such as phosphate-based peroxide stabilizers increase the Total Organic Carbon (TOC) and Chemical Oxygen Demand (COD) values of effluent. Many dyeing auxiliaries used during dyeing process are non-biodegradable and not recyclables and increase the BOD and COD loads of the effluents. Carriers used to facilitate dyeing of polyester under milder conditions are toxic and may affect the health of workers besides creating problems in effluent problem [37]. On the other hand, the dry and environment friendly plasma treatment on fibre surface neither employs harmful chemical solutions, nor generates contaminated water. Moreover, such treatments do not create mechanical hazards for treated fabrics. [38-40]. The technology significantly reduces pollution caused by residual chemicals. In addition, plasma is able to modify the substrate surface properties, such as micro roughness and induce chemically active functional groups, without affecting bulk properties of the substrate. Due to improved water absorption of fabric, the efficient plasma treatment reduces the amount of chemicals needed in conventional processing with better exhaustion of chemicals from the bath [41]. Plasma treatment also enjoys the advantage of consuming less energy over the conventional methods. Gal et al. [42] investigated the energy consumption and by-product generation of the non-thermal plasma chemical NO-reduction process. They observed an extremely low energy consumption of less than 150 eV per molecule for NO reduction by the discharge plasma treatment.

Conclusion

The dominant role of plasma surface treatment to improve the properties of textile materials is reviewed. The properties of the textile materials which are enhanced include wettability, adhesion, biocompatibility, protection and anti-wear, sterilization and chemical affinity or inertness. The textile and clothing industries, globally, are facing some big challenges today mainly because of globalization. The growing environmental and energy-saving concerns will lead to the gradual replacement of many conventional wet processing methods using large amount of water, energy and effluents, by various forms of low liquor and dry-finishing processes. Plasma technology has a strong potential to offer in an attractive way achievement of new horizons in the field of textile technology [43].

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