Ultrasonic Textile Dyeing and Dyes Decoloration; An Environment Friendly Technique

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Abstract

The ultrasound is one of the green approaches to words green technology. Utilization of ultrasound in textile wet processing provides enormous advantages. The use of ultrasonic in dyeing provides lots of time demanded advantages such energy savings, reduced processing times, environmental improvements, process enhancement, and lower overall processing costs. Beside the above mentioned advantages ultrasound also offers some added advantages i.e. ultrasound alters the fiber structure to increase adsorption and also significant enhancements in diffusion coefficient of the chemical molecules and the dye particles in the aqueous solutions can be found. Only fundamental technological knowhow of the operation is needed for meaningful application of ultrasonic in textile processing. In this work ultrasound and its potential application in textile wet processing specifically in dyeing and in waste water treatment is reviewed.

Keywords: Ultrasonic dyeing, sono-chemistry, sonolysis, dyes degradation, de-coloration.

1. Introduction

Textile wet processing involving the use of huge amount of chemicals and auxiliaries for aiding, quickening or hindering the rates of the processing which are conducted at different temperatures to transfer mass from the processing medium to the surface of the textile material. All chemical processes are time and temperature dependent and compromising either could affect product quality[1]. The use of ultrasonic frequency in textile wet processing provides us lots of significant advantages. Ultrasound assisted pretreatment decrease the fiber degradation while the qualities such as degree of whiteness and wet ability of the cellulosic fabric remain same. The same criteria are also applied for other fibers including synthetic fiber. The mercerization of cellulosic material using ultrasound shows 35% increasing in fiber diameter[2]. The use of ultrasonic energy in dyeing optimizes the dyeing process. Moreover, it can be used for dyeing both hydrophilic and hydrophobic fibers. Dyeing using ultrasonic technique at $50^{o}C$ given slightly higher color strength values than those obtained using

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conventional dyeing method at 80^{O}C[3]. The utilization of ultrasonic wave for cold pad-batch dyeing decreased the batching time at minimum quantity of alkali concentration. Knitted interlock fabric dyed at 600 kHz ultrasonic frequencies, temperature (30-50^{O}C) and salt concentrations 60g/dm^{3} showed deeper hue in comparison with that achieved by conventional method[4].

2. Basic of Ultrasound

Ultrasound (US) is sound frequency above 20 kHz. A significant enhancement can be found in mixing, shearing and mass transfer during the application of ultrasonic frequency to an aqueous solution. Under certain conditions cavitation i.e. formation of bubbles in liquid due to movement of object is produced which demonstrate itself in the production of tiny bubbles which collapses violently inward to produce so called “hotspots” which tend to generate highly reactive hydroxyl radicals and unusual chemical transformations[5].

As early as 1927 Loomis found the chemical and biological effects of ultrasound[6]. Ultrasound spans the frequencies of roughly 18 kHz-10 MHz beyond human hearing. Three distinct uses of ultrasound: low frequency or conventional power ultrasound (20-100 kHz), medium frequency ultrasound (300-1000 kHz) and diagnostic or high frequency ultrasound (2-10 MHz) have been reported in different research work[7, 8].

Ultrasonic waves can be focused, reflected and refracted same as the other electromagnetic waves; but they require a medium with elastic properties for propagation which is not applied to other electromagnetic waves. Acoustic energy is a mechanical energy and it is not absorbed by molecules.

During the passing of ultrasound through a liquid it induces vibrational motions of the intermolecular bonds, and energy is thus transferred through the medium in the propagational direction[7]. Different physical mechanisms are responsible for producing chemical effects by ultrasound. Cavitation is the most important nonlinear acoustic process for sonochemistry.

Ultrasound waves comprises both expansion and compression cycles. Compression cycles employ a positive pressure on the liquid and push molecules together, while expansion cycles employ a negative pressure and pull molecules apart. During the expansion of a sound wave cycle with sufficient intensity cavities can be generated. ‘‘Voids’’ are resulting in the liquid as a consequence. Sound waves intensity is needed to induce cavitation based on the type and purity of the liquid. Pure liquids exhibit great tensile strength; as a result ultrasonic generators cannot produce significant negative pressures to create cavities. Enormous amount of small solid particles, dissolved gases are contained in impure liquid which are responsible for the reduction of tensile strength of the liquid. Nucleation of the bubbles occur weak points in the liquid which are created by those solid particles and gas bubbles [6, 9-14].

A bubble in irradiated liquid continually absorbs energy from alternating compression and the expansion cycles of the

sound wave. This causes the bubbles to grow in expansion cycles and contract in compression cycles. Most familiar two forms of cavitation are: stable and transient. High-intensity acoustic field is responsible for producing transient cavitation. A transient cavity has a lifetime of one, or at most, a few acoustic cycles. A bubble grows very rapidly to double its initial size and, finally, collapses violently in less than a microsecond. On the other hand, bubbles size oscillates in phases with the expansion and compression cycles at lower acoustic cycle. The bubble grows slowly over many acoustic cycles. This classification of cavitation is not strict, however, stable cavitation can lead to transient cavitation or a transient cavity can produce very small bubbles that undergo stable cavitation[6, 9, 11, 13, 15]. The critical sizes of the bubble depend on the liquid and the frequency of the sound. At 20 kHz the size of the bubble is roughly 170 mm and at 1 MHz it is 3.3 mm[10].

Unusual environment for chemical reactions is created by the collapse of acoustic cycle. During cavity collapse vapor and gases inside the cavity are extremely compressed. Significant increases in temperature and pressure are resulted from the acoustic cycle collapse[11]. Drastic local conditions: temperatures of about 5500 C inside the bubble and 2100 C in the liquid that surrounds the cavity and pressure up to 100 MPa within the collapsing cavity are occurred as a result of cavitational collapsing[10]. Such conditions are limited to a very small region and the heat produced during cavitation is dissipated very quickly (heating and cooling rates greater than 109 K/s). As a result, the surrounding liquid remains at the ambient temperature. In this condition organic compounds are highly degraded and inorganic compounds can be oxidized or reduced. Decomposition of the water molecules into extremely reactive radicals $HO^{\cdot}$ and $H^{\cdot}$ can be occurred by ultrasonic degradation. During the cooling phase these decomposed products can recombine and form hydrogen peroxide and molecular hydrogen [8, 11, 12].

3. Ultrasonic chemical reaction

Though several theories regarding sonochemical events are available, each theory is based on acoustic cavitation. The most familiar and excepted model is ‘hot-spot’ model. The ‘hot spot’ model states that each microbubble acts as a small micro reactor which, during the collapse, produces different reactive species and heat. The model proposed three regions for the occurrence of chemical reactions: a hot gaseous nucleus, an interface between the bubble and the bulk liquid, and the bulk media. Free radicals or/and excited states are formed from water dissociation, vapors and gases or various substrates during bubble collapse, where high temperatures and pressures provide activation energy for homolytic bond breakage. The resulted radicals either react with each other to form new molecules and radicals, or diffuse into bulk liquid to serve as oxidants. Combustion and free-radical reactions occur in the liquid shell surrounding the hot bubble. This area was estimated to have extended w200 nm from the bubble’s surface and had a lifetime of 12 ms[12, 16]. **T**his region of low polarity

allows hydrophobic solutes to accumulate readily. The bulk media is the major reaction site for hydrophilic compounds where they might be effectively destroyed by oxidative degradation, provided that sufficient quantities of hydroxyl radicals are ejected into the solution during cavity collapse. During the 'transient' collapse of bubbles maximum radical transfer occurs. Intense shock waves and enormous shear forces are generated on the bubbles collapse in the bulk media.

Application of sonochemistry mainly involves with homogeneous reactions of liquid. Reactions involving solid/liquid interfaced heterogeneous reactions are also very important. There are two types of reactions involving solids and liquids; one in which the solid is a reagent and another in which it is a catalyst. Cavitational collapse has two forms of influence in heterogeneous systems. Direct erosion on the solid's surface itself caused by shock waves produced on cavity implosion. On the other hand, cavitational collapse close to a solid surface is markedly asymmetrical which generates a jet of liquid directed at the surface with a speed in the order of 110 m/s. This represents the well-known cleaning action of ultrasound. The micro jets phenomenon can also be used to produce very fine emulsions from immiscible liquids. A good example is the hydrolysis of commercially important oils, fats and waxes in aqueous sodium hydroxide.

4. Application in textile dyeing

Ultrasound assisted wet processing in textile industry become popular day by day due its enormous advantages like process acceleration and attainment of the same or better results than existing techniques under less extreme conditions, i.e., lower temperature and lower chemical concentrations. Thakore et al. compiled a review of application of ultrasound in textile wet processing industry[17]. Several studies show the utilization of ultrasonic frequency in the pretreatment of textile industry i.e. preparation of sizes, emulsions, dye dispersions and thickeners for print paste. Though the excellent result can be achieved by the ultrasonic frequency in laboratory scale, the matter of exclamatory is that it is still not implemented in industrial scale.

Textile material is fundamentally a porous viscoelastic material made of either natural or synthetic fibers. Datar and Moholkar shows the acoustic behavior of textile material when it subjected under low and high intensity ultrasound frequency[18, 19]. Mass transportation are limited to diffusion and convection of the pores existed in inside and outside of the yarn. The improvement of processing in textile industry are mainly depends on the intensification and acceleration of mass transport specially in the intra-yarn pores Mass transport magnification exploiting a usual approach like high temperatures, is not always feasible, because of the undesired side-effects such as fabric damage.

Mass transport intensification in washing processes by the use of power ultrasound was investigated by Warmoeskerken and co-workers[20]. The key findings of this study were that application of ultrasound increases the mass transfer by decreasing the stagnant

cores in the yarns. Outcomes of this study suggest that the practice of an ultrasonic bath, frequency 33kHz, intensified the rinsing of NaCl by a factor of 6.

Besides the above mentioned investigation, Moholkar and Warmoeskerken studied the relationship among the effectiveness the ultrasound in textile washing and the process parameters such as: the position of the textile in the ultrasound wave field, the gas content of the textile and the washing medium[21]. Outcomes show that acoustic cavitation and the associated effects, such as the generation of micro jets are the principle physical mechanisms behind the ultrasonic textile washing process. Moreover, they established a simple semi-empirical methodology for assessment of mass transfer improvement[22].

Vouters et al. investigated the de-oiling of polyamide and de-sizing of cotton under the ultrasonic frequency in laboratory scale[23]. The key objects of this investigation were to produce an ultrasonic energy device which could be customized onto the jigger. Outcomes scrutinized that ultrasound technology exemplifies an encouraging technique for intensifying diffusion and washing by the effect of cavitation, as well as for enhancing the efficiency of processes when compared to conventional treatments, in particular de-oiling treatments. Utilization of these processes at the industrial scale requires further modification.

Sokolov and Tumansky were introduced ultrasound in textile dyeing for the first time in 1941. Over the time, enormous number of investigation has been done using high different scale frequency to investigate the effects of ultrasound on dye dispersion quality, change in solubility of water soluble dyes and dye uptake by textile materials using a broad spectrum of natural and synthetic fibers. Significant improvements witnessed in dyeing processes assisted by ultrasound are generally attributed to cavitation phenomena and, as a result, other mechanical effects are produced i.e. dispersion, degassing, diffusion and intense agitation of the liquid

Many researchers demonstrate the dyeing rates acceleration which might be the cumulative effects of the aforementioned phenomenon. Dye molecules exhibits a property of propensity to form aggregates in the solution and this propensity intensifies with the increasing relative molecular mass of the dye molecule, but the elevation in temperatures trigger disaggregation. It is familiar that ultrasonic energy is responsible for the decomposition of the dye aggregates in a solution, thus keeping it in a mono-molecular state. Cavitation and its physico-chemical results enhancements in the dyeing rate and economize on energy and process time consumption. Lee and Kim investigate changes in the particle size of the disperse dye C.I. Disperse Red 60 in a low frequency ultrasound field (26 kHz), and the effect of particle size on the exhaustion rate[24]. The size of particle was in the range of 1-2 mm increased from 63 to 80%, those in the range of 4-10 mm from 10 to 16%, whereas particle sizes in the range of 65-72 mm decreased from 14 to approximately 0% during 1 h of ultrasound irradiation. The volume of small particles increased, whereas

those of large particles decreased relatively. Outcome of this research scrutinized that ultrasound decrease the particle size of disperse dye and enhances the dye fixation.

Thakore et al. investigates the diffusion and permeability of direct dyes through a cellophane film using a low frequency ultrasound of 20 kHz[25]. In the investigation they use C.I. Direct Red 81. The investigation scrutinized a significant improvement in both diffusion and permeability coefficient.

The dyeing of silk by using cationic, acid and metal-complex dyes at low temperatures, using low frequency ultrasound of 26 kHz was investigated by Shukla and Mathur[26]. As a part of this study the obtained result was compared with the results obtained by traditional processes. The key findings of this findings of this study are that ultrasound assisted silk dyeing enhances the dye uptake for all types of dyes at lower dyeing temperatures and shorter process time, in comparison with conventional dyeing at 85ºC for 60 min

Dyeing of polyester fibers with disperse dyes assisted by ultrasound and effects of ultrasound was investigated by Saligram et al.[27]. Swollen and unswollen PBT and PET fibres were dyed with and without low frequency ultrasound under different conditions regarding time and temperature. Aforementioned investigation shows that significant improvement in dye molecules diffusion into fibers can be achieved ultrasound assisted dyeing but the uniformity is not as good as the traditional process. The investigation also exerts that enhancement in dye uptake can be achieved by the addition of carrier. The effect of a carrier and ultrasound together was significantly larger than either individually. Ahmad and Lomas also perform the study similar to aforementioned study. The impact of ultrasound on the dyeing characteristics of PET fibres is studied by using C.I. Disperse Red 60 which has a highly crystalline structure and C.I. Disperse Blue 56 with a poor crystalline structure by Lee et al.[28]. A series work of this investigation[24] shows that ultrasound has a remarkable effect on the reduction in particle size of C.I. Disperse Red 60. A close observation of this study[28] verifies this fact for C.I. Reactive Red 60, but the matter of concentration is that there is no remarkable impact attributed to ultrasound on dye uptake and dyeing rate for C.I. Disperse Blue 56.

Dyeing of cellulosic fabrics with reactive dyes (C.I. Reactive Red 120 and C.I. Reactive Black 5) assisted by ultrasound was investigated by Oner et al.[29]. Dyeing was carried out both conventionally and by ultrasonic techniques. The exhaustion percentage, amount of dye transferred to the washing bath after dyeing, fastness properties and color strength were compared. Improvement in dyes fixation, exhaustion for both reactive dyes in ultrasonic method are shown by this study but there is no improvement in terms of fastness properties. Improvements in dye uptake on cotton were observed by another study by Mock et al. shows significant improvement in uptake of direct dyes in cotton[30]. Cotton was dyed with the direct

dyes Solophenyl Blue FGL 220 and Solophenyl Scarlet BNL 200. Both dyes needed a relatively large amount of salt for exhaustion. The key findings of this are that dyeing of cotton fabrics with direct dyes assisted by ultrasound requires less salt than the traditional process, significant reduction energy consumption can be achieved as low temperature and less process time required.

Shimizu et al. studied the application of ultrasound in dyeing of nylon for the first time[31] and later similar investigation was carried out by Kamel et al.[32, 33]. It scrutinized that nylon-6 fiber is very vulnerable to low frequency ultrasound-assisted dyeing with various types of dyes at various temperatures and various reaction conditions. Dyeing of nylon with disperse, acid, acid mordant and reactive dyes in a low ultrasound field (27 kHz and 38.5 kHz) were investigated. Significant increasing in dyeing rate but decreases in activation energies was found. Kamel also established that dye uptake is enhanced in the phase of dyeing diffusion. These studies results confirm the outcomes of other authors that the enhancing effect is attributed to de-aggregation of the dye molecules, which leads to better dye diffusion and possible assistance for dye to fiber bond fixation.

5. Ultrasound in dyes de-coloration

Application of ultrasound has already gained popularity in environmental remediation due to the formation of highly concentrated oxidizing species such as hydroxyl radicals ($HO^{\cdot}$), hydrogen radicals ($H^{\cdot}$), hydroperoxyl radicals ($HO^{\cdot}_2$) and H_2O_2, and localized high temperatures and pressures. Sonochemical effects like pyrolytic and radical reactions have been observed between the 20 kHz and 1 MHz frequency range. The highest efficiencies were reported above 200 kHz. In the low frequency range between 20 kHz and 100 kHz, the hydromechanical effects such as shear forces and jet-streams are predominated[34]. Several research works reported the effective use of ultrasonic irradiation for the decolouration of various textile dyes but the total mineralization of these complex compounds is difficult to obtain with ultrasound alone.

Adewuyi[12] has already gathered studies involving the use of sonochemical or photo sonochemical processes to treat a variety of chemical contaminants such as aromatic compounds, chlorinated aliphatic hydro-carbons, explosives, herbicides and pesticides, organic dyes, organic and inorganic gaseous pollutants, mostly in aqueous media. In the textile industry these are very interesting and encouraging results in the decolouration and mineralization of the azo dyes Remazol Black B (investigated by Vinodgopal et al.) and Naphthol Blue Black (investigated by Stock et al.) after long exposure to high frequency ultrasound. It seems that the ultrasound-assisted decolouration and mineralization of textile dyes has become quite an interesting research area confirmed by several reports over the last few years. Ince NH and Tezcanli G. [38] show reactive dyestuff degradation by combined sonolysis and ozonation at 520 kHz piezoelectric transducer (1.63 W/cm2), ozone 3.36 g/L, flow rate 50 L/h, air, T = 20 G 0.5 C, 600 mL of 10, 20, 40, 50, 60 mM areated dye solutions, pH = 7, contact time at least 20 min and the colour removal using US/O_3 twice as fast than with O_3. Vinodgopal K and Peller J. show the determination of

intermediates and end products by sonolysis and g-radiolysis 640 kHz transducer type, O2, 82 mM dye solution and -hydroxybenzenesulfonic acid,1,2-naphthaquinone were detected as intermediates oxalate and formate ions were the most probable end products after 6 h [35]. Mrowetz M et al. investigate degradation and mineralization rates at different initial acid dyes concentrations and amount of photocatalyst by sonolysis and photocatalysis, sonophotocatalysis and found the greatest rate constant was achieved by sonophotocatalysis at different initial dye concentrations and amount of TiO_2 and with increasing dye concentration at constant amount of TiO_2 reaction rate decrease or stay constant in the case of US + TiO_2 treatment[36]. Ge J and Qu J. study degradation of the dye on MnO2 in the presence of US under O2 or Ar atmosphere at 50 kHz, 150 W cleaning bath, MnO2-surface area 29.3 m2/g, T = 22 C, 100 mL of the dye solution with concentration 100 mg/L and pH = 3, 1 or 2 g/L MnO2, pre-aerated for 20 min with O2 or Ar with a flow rate of 100 mL/min, contact time for US 240 min and found US enhanced decolouration of the dye on MnO2 from 77.03% (MnO2 alone) to 92.88% (US + MnO2, O2) and 98.93%, US may induce the de-aggregation of the photocatalyst and increase its surface area, US accelerate mass transport between the solution phase and the photocatalyst surface, US increases the amount of radicals through cavitation phenomena (US + MnO2, Ar) and US reduced the particle size of MnO2 and consequently increase the active surface area[37]. Tezcanli-Guyer G and Ince NH show more than 80% decolouration of all dyes was achieved within 120 min by sonolysis 520 kHz plate type piezoelectric transducer, 0.126 W/mL, 300 mL 20 mg/L dyes solutions aerated for 1 h with pH = 5.5-6.5, contact time 4 h, Ar with flow while for any reduction of absorbance in UV region longer contact time is needed (4 h)[38].

6. Conclusion

Textile industry is the world's second largest industry just after the food industry. It consumes a larger share of productive energies. Longer process time, consumption of huge energy and water, less efficiency in processing, environmental pollution are the main disadvantages of this industry. A lot of research works are going on to overcome these challenges. Utilization of ultrasound in textile industry is a significant advancement. This review showed that the work in this area over the past fifty years has enough promise for application to commercial scale processes. Benefits may include saving in energy, reduction in consumption of chemicals and/or dyes, reduction in process time, improvement in quality and easier process control. Among all wet processes, application to the dyeing process seems to be most advantageous because it currently is the most expensive process. Washing being the least expensive process, the use of ultrasound may or may not be advantageous in terms of saving money.

Nowadays, several researchers are working for resolving the environmental problem caused by the textile industry. Many researchers show that utilization of ultrasound in solving environmental problems specifically in waste water treatment has greater potentiality. This process works on the principle of generating free radicals and their subsequent attack on the contaminant molecules with the aim of either, completely mineralizing the contaminants or converting it into less harmful or lower chain compounds which can then be treated biologically.

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