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Alternative and Emerging Technologies for an Energy-Efficient, Water-Efficient, and Low-Pollution Textile Industry

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Abstract

Emerging energy-efficiency, greenhouse gas (GHG), and pollution mitigation technologies will be crucial for the textile industry as it responds to population and economic growth that is expected to spur a rapid increase in textile consumption over the coming decades and a corresponding increase in the industry's absolute energy use and GHG and other pollutant emissions. This report gives an overview of textile industry processes and compiles available information on the energy savings, environmental and other benefits, costs, commercialization status, and references for 18 emerging technologies to reduce the industry's energy use and environmental emissions. Although studies from around the world identify a variety of sector-specific and cross-cutting energy-efficiency technologies that have already been commercialized for the textile industry, information is scarce and/or scattered regarding emerging or advanced energy-efficiency and low-carbon technologies that are not yet commercialized or at the very early stage of adoption. This report is intended to be a resource on these emerging technologies for engineers, researchers, investors, textile manufacturers, policy makers, and other interested parties.

Contents

Acronyms

CO_2	carbon dioxide
COD	chemical oxygen demand
dpi	dots per inch
eV	electron-volt
Hz	Hertz
ITMA	International Textile Machinery Association
kg	kilogram
keV	kiloelectron-volt
kHz	kilohertz
m	meter
m^2	square meter
MeV	megaelectron-volt
MHz	megahertz
mm	millimeter
mPas	mega-Pascals
U.S. DOE	United States Department of Energy

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1. Introduction

The textile industry uses large amounts of electricity, fuel, and water, with corresponding greenhouse gas emissions (GHGs) and contaminated effluent. With regard to energy use, the textile industry's share of fuel and electricity use within the total final energy use of any one country depends on the structure of the textile industry in that country. For instance, electricity is the dominant energy source for yarn spinning whereas fuels are the major energy source for textile wet processing.

In addition to using substantial energy, textile manufacturing uses a large amount of water, particularly for wet processing of materials, and produces a significant volume of contaminated effluent. Conserving water and mitigating water pollution will also be part of the industry's strategy to make its production processes more environmentally friendly, particularly in parts of the world where water is scarce.

In 2010, the world's population was 6.9 billion; this number is expected to grow to 9.5 billion by 2050 (UN/DESA 2012). The bulk of this growth will take place in underdeveloped and developing countries. As the economy in these countries improves, residents will have more purchasing power; as a result, per-capita consumption of goods, including textiles, will increase. In short, future population and economic growth will stimulate rapid increases in textile production and consumption, which, in turn, will drive significant increases in the textile industry's absolute energy use, water use, and carbon dioxide (CO_2) and other environmentally harmful emissions.

A number of studies have documented the potential for the global textile industry to save energy by adopting commercially available energy-efficiency technologies and measures (Hasanbeigi 2010, Carbon Trust 2005, CIPEC 2007, ECCJ 2007). However, in view of the projected continuing increase in absolute textile production, future reductions (e.g., by 2030 or 2050) in absolute energy use and CO_2 emissions will require innovation beyond technologies that are available today. The same is true for water conservation and reducing other pollutant emissions from the manufacturing process. Developments will likely include new processes and materials as well as technologies that can economically reduce the industry's energy use and emissions. Deployment of these new technologies in the market will be critical to the industry's climate-change mitigation and environmentally friendly production strategies for the mid and long term.

The studies listed above have identified energy-efficiency technologies for the textile industry that are already commercially available, and other studies (e.g., U.S. DOE/AMO 2012) have identified cross-cutting efficiency technologies that, although not specific to the textile industry, are applicable to this industry. However, information is limited and not easily accessible regarding alternative and emerging or advanced energy-efficiency, low-carbon, water-conservation, and pollution-reduction technologies for the industry that have not yet been fully commercialized. This report consolidates the available information on emerging technologies for the textile industry to assist engineers, researchers, investors, textile companies, policy makers, and other interested parties. Although adoption of specific technologies in any given region around the world is driven by local conditions – economic viability, raw materials availability, the type of energy type used and its cost, and the regulatory regime – this report is intended to be of use to a wide audience.

The information presented in this report is collected from publicly available sources and covers the main emerging technologies for an energy-efficient, water-efficient, and low-emission textile industry, but the list of emerging technologies addressed here is not exhaustive.

The report organizes the information presented about each technology in a standard format:

- Description of the technology, including background, theory, pros and cons, barriers and challenges, and case studies if available;
- Energy, environmental, and other benefits of the technology, as well as cost information if available;
- Block diagram or picture if available; and
- Commercialization status of each technology as well as resources for further information.

The commercialization status of each technology is as of the writing of this report and uses the following categories:

- Research stage: The technology has been studied, but no prototype has been developed.
- Development stage: The technology is being studied in the laboratory, and a prototype has been developed.
- Pilot stage: The technology is being tested at an industrial scale at one plant.
- Demonstration stage: The technology is being demonstrated and tested at an industrial scale in more than one plant but has not yet been commercially proven.
- Commercial with very low adoption rate stage: The technology is proven and is being commercialized but has a very small market share.

Table 1 lists the 18 technologies covered in this report, the section of the report in which each technology is discussed, and the technology's commercialization status.

This report is solely for informational purposes. Many emerging technologies are proprietary and/or the manufacturers who are developing new technologies are the primary sources of information about those technologies. Therefore, in some cases, we identify the company that is the source of a technology so that readers, if they wish, can seek out more information about the company and product. Emerging technologies continually change, so the information presented in this report is also subject to change. If readers are aware of a new technology that is not presented in this report or have updated information about a technology in this report, please contact the author.[1]

Table 1. Emerging energy-efficiency, water efficiency, and low-pollution technologies for the textile industry

No.	Technology Name	Commercialization status
	Man-made fiber production technology	
1	Nanoval technology	Pilot
	Spinning	
2	Vortex spinning and jet spinning	Commercial with very low adoption rate
3	Friction spinning	Commercial with very low adoption rate
	Weaving	
4	Multi-phase loom	Commercial with very low adoption rate
	Wet processing	
5	Enzymatic treatments	Various commercialization stages depending on the application
6	Ultrasonic treatments	Pilot
7	Electron-beam treatment	Development
8	Ozone for bleaching cotton fabrics	Development
9	Advanced cotton fiber pre-treatment to increase dye receptivity	Pilot
10	Super-critical CO_2 in dyeing	Pilot
11	Electrochemical dyeing	Development
12	Ink-jet (digital) printing	Commercial with very low adoption rate
13	Plasma technology	Pilot
14	Foam technology in textile finishing	Commercial with very low adoption rate
15	Microwave energy	Development
16	Alternative textile auxiliaries	Various stages of commercialization depending on the type of auxiliary
	Sensor and control technologies	
17	Fuzzy logic and other expert systems	Various stages of commercialization depending on the application
18	Real-time on-line monitoring systems	Pilot

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2. Brief description of textile production processes

The subsections below give a brief overview of textile industry manufacturing processes, and energy use.

2.1.Textile processes

The textile industry has complicated industrial chains. The textile sector is fragmented and heterogeneous, dominated by small and medium enterprises. Demand is driven by three dominant types of end products: clothing, home furnishings, and industrial products. The variety of substrates, processes, machinery, components, and finishing steps involved in producing such a wide range of end products make it difficult to characterize the industry as a whole. Fibers and yarns, methods of fabric production, and finishing processes (preparation, printing, dyeing, chemical/mechanical finishing, and coating) interrelate to produce a finished fabric. Changing one of these components affects the properties of the end product, which include weight, appearance, texture, strength, luster, flexibility, and affinity to dyestuff.

Figure 1 is a generalized flow diagram depicting the various textile processes that are involved in converting raw materials into a finished product. These processes do not occur at a single facility although some integrated plants house several steps of a process in a single plant. There are also several niche areas and specialized products that may entail special processing steps not shown in Figure 1 (U.S. EPA 1998).

Due to the variety of the processes involved in the textile industry, the reader is referred to Hasanbeigi (2010) for brief descriptions of the major textile processes for which energy-efficiency and other measures are presented in this report; that report contains flow charts of the processes to help the reader understand manufacturing sequences and process steps.

The major textile processes that are discussed in the guidebook are:

- Spun yarn spinning
- Weaving
- Wet processing (preparation, dyeing, printing, and finishing)
- Producing man-made fibers

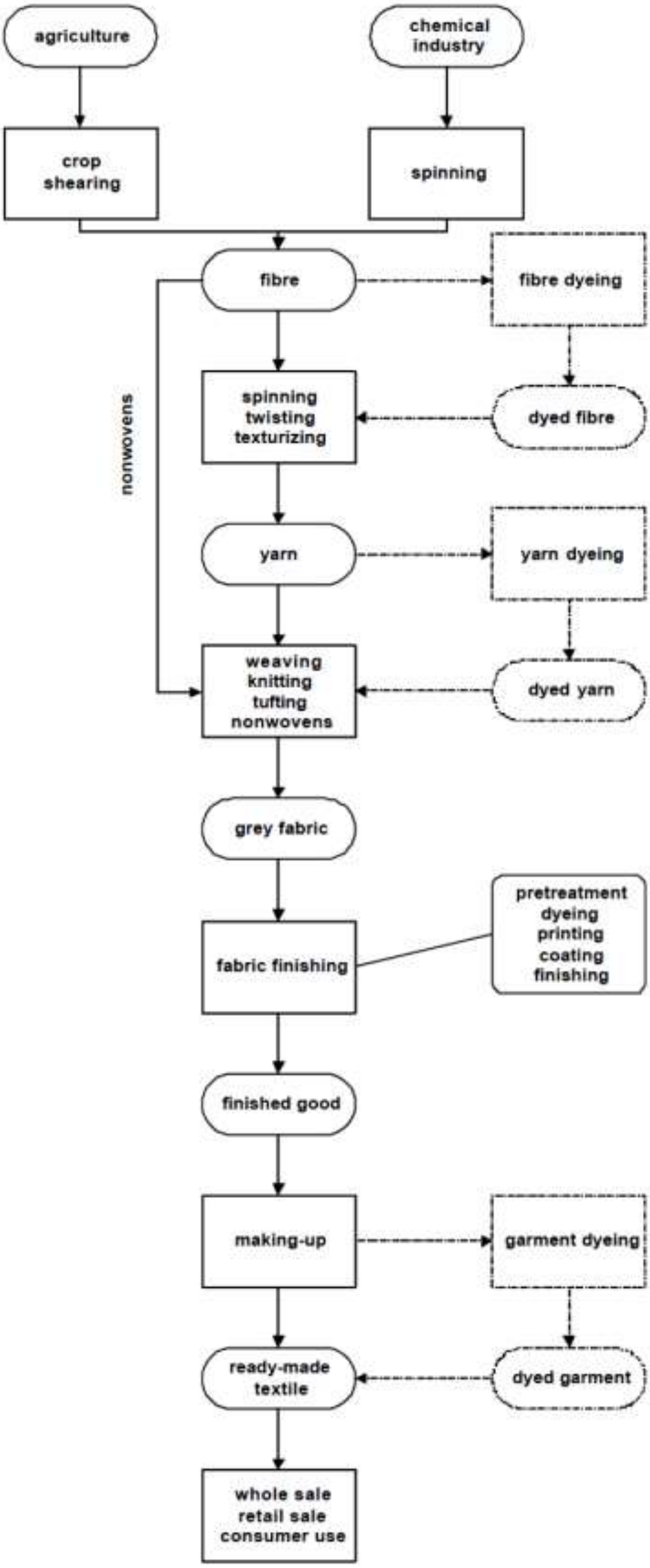


Figure 1. The textile chain (Schönberger and Schäfer 2003)

2.2. Energy use in the textile industry

Although the textile industry is not considered an energy-intensive industry, it comprises a large number of plants that, together, consume a significant amount of energy. The share of total manufacturing energy consumed by the textile industry in a particular country depends upon the structure of the manufacturing sector in that country. For instance, in 2010, the textile industry accounted for about 4% of total manufacturing final energy use in China (NBS 2011) but less than 2% in the U.S. (U.S. DOE 2010). Manufacturing census data from 2010 in the U.S. shows that 53% of the final energy used in the U.S. textile industry was fuel energy and 47% was electricity (U.S. DOE 2013). The U.S. textile industry is also ranked as the 6th largest steam consumer amongst 15 major industrial sectors studied in the U.S. The same study showed that around 48% of the energy input to the textile industry is lost onsite (e.g. in boilers, motor system, distribution, etc.) (ORNL 2012).

2.2.1. Energy use breakdown by end use

In a textile plant, energy is used for different purposes. Figure 2 shows the breakdown of final energy use by end use in the U.S. textile industry in 2006 (ORNL 2012). The percentages shown in Figure 2 will vary from one country to another. For example, it is likely that the textile industry in the U.S. does not include as many labor-intensive processes (e.g., spinning and weaving) as are found in some developing countries (e.g., China and India) where the cost of labor is lower. As shown in Figure 2, process heating and motor-driven systems accounted for the largest shares (50% and 26%, respectively) of end-use energy use in the U.S. textile industry in 2006.

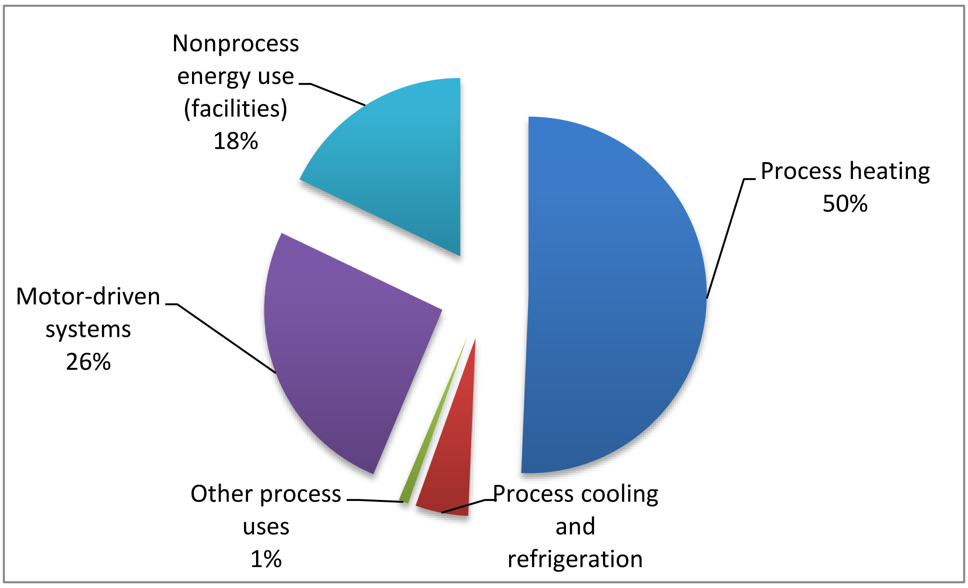


Figure 1. Final energy end uses in the U.S. textile industry in 2006 (ORNL 2012)

A significant amount of energy is lost, or wasted, within the textile manufacturing process. Figure 3 shows the on-site energy loss profile for the U.S. textile industry (U.S. DOE 2004). Approximately 48% of the energy input to the U.S. textile industry is lost on site. Motor-driven systems account for the largest share of on-site energy loss (16%). The loss profile could vary for the textile industry in other countries depending on the structure of the industry in those countries.

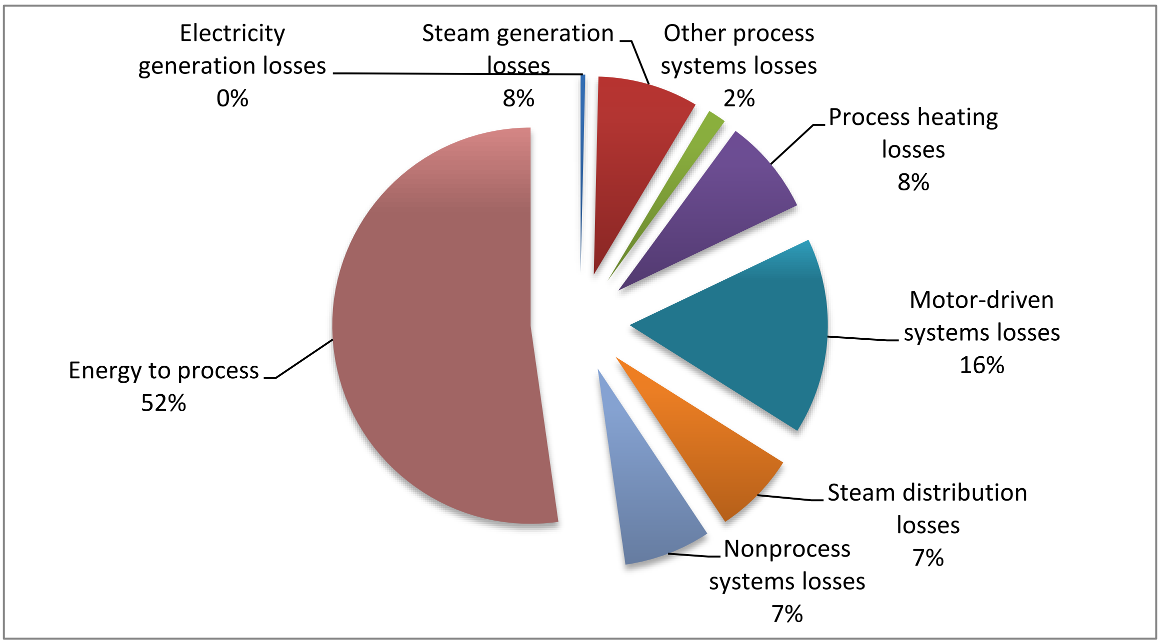


Figure 2. On-site energy loss profile for the U.S. textile industry in 2006 (ORNL 2012)

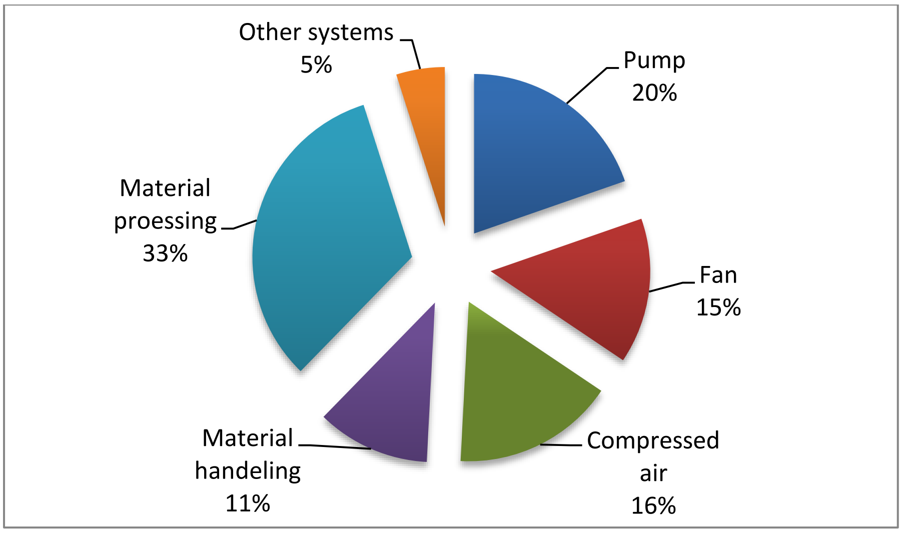


Figure 3. Breakdown of motor systems energy use in the U.S. textile industry in 2006 (ORNL 2012)

Figure 2 shows that motor-driven systems are major end-use energy consumers in the textile industry and Figure 3 shows that these systems also account for a large share of energy lost in the industry. Figure 4 shows the breakdown of the energy used by motor systems in different processes in the U.S. textile industry. Material processing accounts for the largest share of the energy used by motor-driven systems (33%), followed by pumps, compressed air, and fan systems (20%, 16%, and 15% respectively). These percentages in other countries will depend on the structure of the textile industry in those countries. For instance, if the weaving industry in a given country uses a much greater fraction of air-jet weaving machines (which consume large amounts of compressed air) than are used in the U.S., the share of total motor-driven system energy consumed by compressed air energy systems would probably be larger than shown in Figure 4.

2.2.2. Breakdown of energy use in composite textile plants (spinning-weaving-wet processing)

A composite textile plant houses spinning, weaving/knitting, and wet processing (preparation, dyeing/printing, finishing) at a single site. Figure 5 shows the breakdown of typical electricity and thermal energy use in a composite textile plant (Sathaye et al. 2005). In Figure 5, spinning consumes the largest share of electricity (41%), followed by weaving preparation and weaving (18%). Wet-processing preparation (de-sizing, bleaching, etc.) and finishing together consume the greatest share of thermal energy (35%). A significant amount of thermal energy is also lost during steam generation and distribution (35%). These percentages will vary by plant.

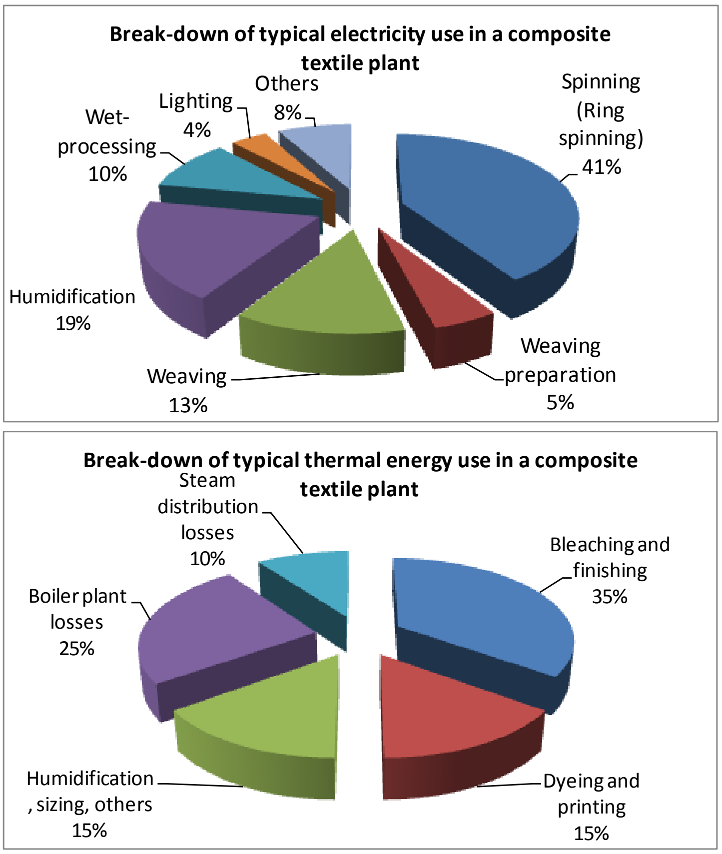


Figure 4. Breakdown of typical electricity and thermal energy use in a composite textile plant (Sathaye et al. 2005)

2.3. Water use and pollutants in the textile industry

The textile industry and especially textile wet-processing is one of the largest consumers of water in manufacturing and hence one of the main producers of industrial wastewater. Also, since various chemicals are used in different textile processes like pre-treatment, dyeing, printing, and finishing, the textile wastewater contains many toxic chemicals which if not treated properly before discharging to the environment, can cause serious environmental damage. In addition, in many countries, the charges for water supply and effluent discharge are increasing. Hence, for companies to save costs and remain competitive, they need to save water and address issues related to wastewater disposal.

EIPPCB (2003) provides a good overview of water consumption and wastewater pollution for different textile wet-processing processes. As an example, Table 2 shows the percentage of unfixed dyes for various textiles. The unfixed dye will be discharged in the effluent after each dyeing process.

Table 2. Percentage of unfixed dye for different dye types and applications (ETBPP 1997)

Fibre	Dye type	Unfixed dye %
Wool and nylon	Acid dyes/reactive dyes for wool	7 - 20
	Pre-metallised dyes	2 - 7
	After chromes	1 - 2
Cotton and viscose	Azoic dyes	5 - 10
	Reactive dyes	20 - 50
	Direct dyes	5 - 20
	Pigment	1
	Vat dyes	5 - 20
	Sulphur dyes	30 - 40
Polyester	Disperse	8 - 20
Acrylic	Modified basic	2 - 3
Polypropylene	Spun dyed	N/A

The quantity and composition of textile industry effluent varies with the type of fiber, the process involved, and the way that process is operated. Table 3 summarizes the published data for combined effluent from the processing of cotton and synthetic blends.

Table 3. Typical effluent characteristics (ETBPP 1997)

Determinand	Woven fabric finishing	Knit fabric finishing	Stock and yarn dyeing and finishing
BOD[1] (mg/litre)	550 - 650	250 - 350	200 - 250
Suspended solids (mg/litre)	185 - 300	300	50 - 75
COD[2] (mg/litre)	850 - 1 200	850 - 1 000	524 - 800
Sulphide (mg/litre)	3	0.2	0 - 0.09
Colour (ADMI[3] units)	325	400	600
pH	7 - 11	6 - 9	7 - 12

[1] Biological oxygen demand
[2] Chemical oxygen demand
[3] American Dye Manufacturers Institute

3. Emerging Energy-Efficiency, Water-Efficiency, and Pollution Reduction Technologies

The subsections below describe emerging technologies that can reduce energy and/or water consumption as well as CO_2 and other emissions associated with different subsectors of the textile industry.

Since wet processing of textiles consumes the largest share of energy and water in the industry and is also the primary source of pollution, most of the research has been focused on developing new technologies for this subsector. Thus, a majority of the 18 technologies presented in this report are applicable to textile wet processing.

3.1. Man-made fiber production

3.1.1. Nanoval technology

Description

The Nanoval process is an alternative technology for production fine man-made fibers by using less energy compared to the conventional spinning technology because it eliminates air heating and air quenching and increases the productivity. This technology is based on a mechanism that produces fine and finest filaments by splitting one melt monofilament into a number (normally around 50, but up to several hundreds) of finer filaments (Nonwovens Industry 2006; Hutten 2007). The monofilaments are picked up directly underneath the spinneret by a gas stream (normally air), which draws them by applying shear stresses to the surface. In contrast to all melt-blown processes, both the melt and air flows are steadily accelerated. As soon as the internal pressure in the monofilament exceeds the external gas pressure, the so-called Nanoval effect causes the filament to burst spontaneously into a multitude of up to several 100 finer filaments per spin hole (NANOVAL GmbH & Co. KG. 2012).

Nonwoven fabrics can be produced from spliced continuous filaments. In this case, the spinneret nozzles are arranged in rows or as single spin-cones in several parallel rows. The filaments can be deposited on a collector belt running below; gas/air is removed from underneath the belt by a suction fan. Filaments can reach diameters smaller than 1 micrometer (µm). Manmade polymers used for nonwovens are mainly polypropylene, polyethylene, polyester, polyamide, and others such as polybutylenterephtalate, polyurethane, and polylactide. Nonwovens made by this technology are used for medical and hygienic webs, filters, wipers, and agricultural webs (NANOVAL GmbH & Co. KG. 2012).

A pilot plant that could produce a 1-meter (m)-wide web has been built, as well as production plants that can manufacture 3.5-m-wide web . The weight of the web produced in these plants varies from 5 to 100 grams per square meter (NANOVAL GmbH & Co. KG. 2012).

Energy/Environment/Cost/Other Benefits

The developer of Nanoval technology claims that it has the following benefits compared to conventional technologies (Nonwovens Industry 2006):

- Use of cold air for spinning, eliminating the need for air heating
- Lower energy consumption compared to what other processes require; the difference in energy consumption compared to conventional technology increases with increase in filament fineness because the compressed air used in Nanoval technology consumes less energy than air heating in conventional technology
- Higher production rate per spinneret
- No need for quenching air for high throughputs and coarse fibers because spinning uses cold air

Block Diagram or Photo

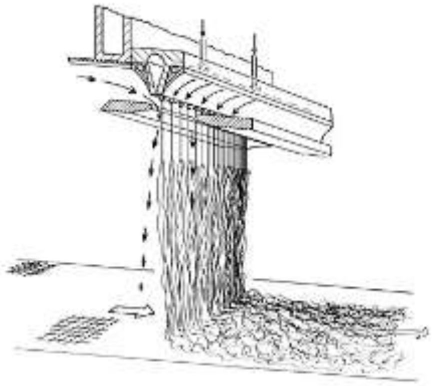


Figure 5. Nanoval process (NANOVAL GmbH & Co. KG. 2012)

Commercial Status

Pilot stage

References for Further Information

NANOVAL GmbH & Co. KG. (2012)

3.2. Spinning

Most new spinning technologies aim to increase productivity, improve or at least retain yarn quality, and ensure increased efficiency in subsequent processing (e.g. weaving, dyeing, and finishing). Introduction of the BD-200 rotor spinner in 1967 did away with the concept of spindle-twisting and established the rotor spinning system for coarse- and medium-count textiles. However, the practical limits to the productivity of this system were encountered when rotor speeds reached 150,000 rotations per minute and rotor diameters had to be reduced to approximately 28 millimeter (mm) to accommodate such high speeds. New systems, such as twistless spinning, air-vortex spinning, and self-twist spinning, were introduced in the late 1960s (Ishtiaque 2003).

Figure 7 shows the production speeds of different spinning technologies. Vortex spinning has the highest production speed, followed by jet spinning and friction spinning. These three emerging alternative spinning technologies are explained in more detail below.

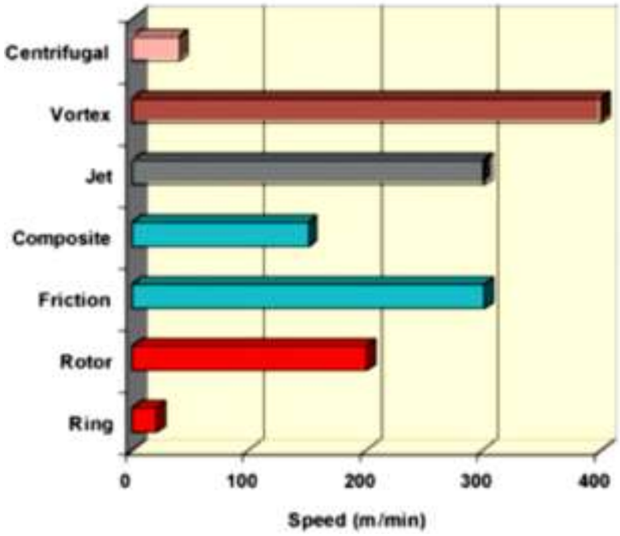


Figure 6. Production speed of different spinning technologies (Oxenham 2003)

3.2.1. Vortex spinning and jet spinning

Description

Two companies, Murata Machinery Ltd. and Rieter, make machines that spin yarn using an air vortex that is created in one nozzle block. Murata's device is called a vortex spinning machine and currently dominates the market. Rieter's new device is called an air-jet spinning machine. The vortex spinning machine has a three-roll drafting system and two jet nozzles that create air vortices rotating in opposite directions. The second nozzle creates a false twist on the fiber bundle that emerges from the front roller. Between the front roller and the first nozzle, which creates an air vortex in the opposite direction, the twist is partially removed and some of the edge fibers separate from the fiber bundle; these edge fibers move through the second nozzle either in untwisted form or with a small twist while the core fibers are guided in twisted form through the second nozzle, which untwists them as it twists the edge fibers. The result, when the yarn leaves the second nozzle, is an untwisted core wrapped by twisted edge fibers. The system is reported to be suitable for processing manmade fibers and their blends with cotton. Because the twist is created by airflow in the vortex spinning system, high-speed rotating mechanical parts are not required, so high production rates are possible (Erdumlu et al. 2012).

The raw materials cost is reportedly higher for vortex spinning systems than for ring and open-end rotor spinning systems; this cost increases further when the material contains many short fibers (Erdumlu et al. 2012). Concerns have been expressed that there is excessive fiber loss using the vortex spinning machine. The fiber loss can be about 8 percent, but most of what is lost is short fiber, which does not contribute to yarn quality (Oxenham 2003). Further research is required to analyze airflow in the yarn formation zone and its impacts on yarn structure, in order to improve product quality, e.g., to produce more even yarns in fine counts and softer fabric handle (Erdumlu et al. 2012).

Murata introduced its third-generation vortex spinning machine, the Vortex III 870, at the

International Textile Machinery Association (ITMA) exhibition in 2011. This machine is available for up to 96 spinning units with a maximum production speed of 500 meters per minute (m/min). At ITMA 2011, Rieter also exhibited J20 air-jet spinning machine, which is double-sided and has 120 spinning units, so it can produce more yarn in a smaller space than other spinning machines. These technologies have higher investment and labor costs than for an open-end rotor spinning system but lower costs than for a ring spinning system (Erdumlu et al. 2012, Oxenham 2002).

Energy/Environment/Cost/Other Benefits

Vortex and jet spinning machines have the following benefits compared to ring and rotor spinning (Erdumlu et al. 2012; Rupp 2012; Oxenham 2011):

- Higher production speed, up to 450 m/min, which means approximately 2-3 times greater productivity than rotor spinning, and 20 - 30 times greater productivity than ring spinning, depending on the yarn count
- Lower energy costs than for both ring and open-end rotor spinning systems, despite the high-pressure air consumption in vortex spinning
- Less hairiness in yarn, resulting in greater abrasion resistance and less pilling than fabrics made from ring-spun or open-end rotor-spun yarns
- For Reiter’s new J20 machine, 25 percent less space required than for ring-spinning equipment producing the same capacity, resulting in reduced building costs and less climate control and space conditioning, which in turn saves energy

Block Diagram or Photo

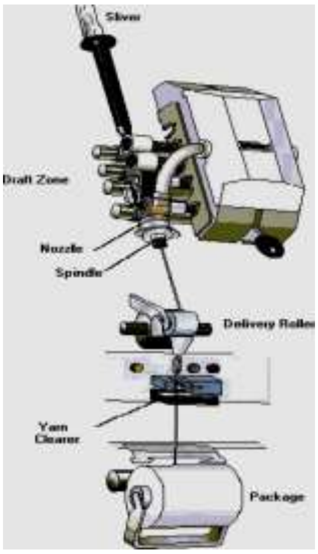


Figure 7. Murata vortex spinning unit (Erdumlu et al. 2012).

Commercial Status

Commercial with very low adoption rate stage

References for Further Information

Erdumlu et al. (2012), Oxenham (2003), Rupp (2012)

3.2.2. Friction spinning

Description

Friction spinning forms yarn with the aid of frictional forces in the spinning zone. Friction-spun yarns are characterized by a distinct wrapper surface. Both man-made and natural fibers and their blends can be used as sheath components. The operations involved in friction spinning generally use three units: the fiber-feeding unit, the yarn-forming unit, and the winding-up unit (Ishtiaque 2003).

The fundamental advantage of the friction-spinning system is that one revolution of the twisting element can generate a number of turns per unit length of yarn. Friction spinning is well established for production of medium- and coarse-count yarns. It has potential for high production speeds and twisting rates and is unique in that it can produce a variety of multi-component yarns, which are preferred for technical textiles. Friction-spun yarns are not normally used to manufacture conventional textiles though they may be used, especially aspile yarns, as weft yarns and for certain knitted goods in which bulk and compressibility are desired. Machines based on the friction spinning principle are Platt Saco Lowell's Master Spinner, DREF-I, DREF-II, DREF-III, DREF-5, DREF-2000, and DREF-3000 (Ishtiaque 2003).

The main drawbacks and limitations of friction spinning are (Ishtiaque 2003; Oxenham 2002):

- Weak yarn due to poor fiber orientation and high twist variation from the surface to the core
- Significant decrease in yarn tenacity at higher spinning speeds
- Greater disorientation and buckling with longer and finer fibers
- Limitation in the fineness of yarns that can be produced because of the large number of fibers required in the yarn cross-section
- Higher end-breakage rate because the number of fibers in the sleeve decreases as the linear density becomes finer, and the incidence of holes in the sleeve increases, thereby increasing the chances of the yarn tail losing contact with the sleeve
- Limitation in maximum production rate of about 300 m/min because of fiber-transport and drafting system speed
- Greater tendency for yarns to snarl than with other spinning methods
- Increase in unevenness and imperfections in yarn as production speed increases
- High compressed-air consumption
- Difficulty holding spinning conditions constant

New developments and modifications are essential to deal with the above limitations, improving friction-spun-yarn quality and extending the count range.

Energy/Environment/Cost/Other Benefits

Friction spinning has the following benefits compared to ring and rotor spinning (Ishtiaque 2003):

- Lower yarn-production and preparation costs and energy use

- Yarn tension independent of speed, so high production speeds, up to 300 m/min, can be attained
- High twist-insertion rates of up to 300,000 rounds/min because of the very low spinning tension
- Greater versatility of fibers used
- Low end-breakage rates therefore greater energy efficiency for spinning process
- Elimination of rewinding step, which saves energy
- Cleaner yarn produced because drums' suction removes dust and trash particles. This increase the efficiency in weaving stage.
- Production of yarns with better handle

Block Diagram or Photo

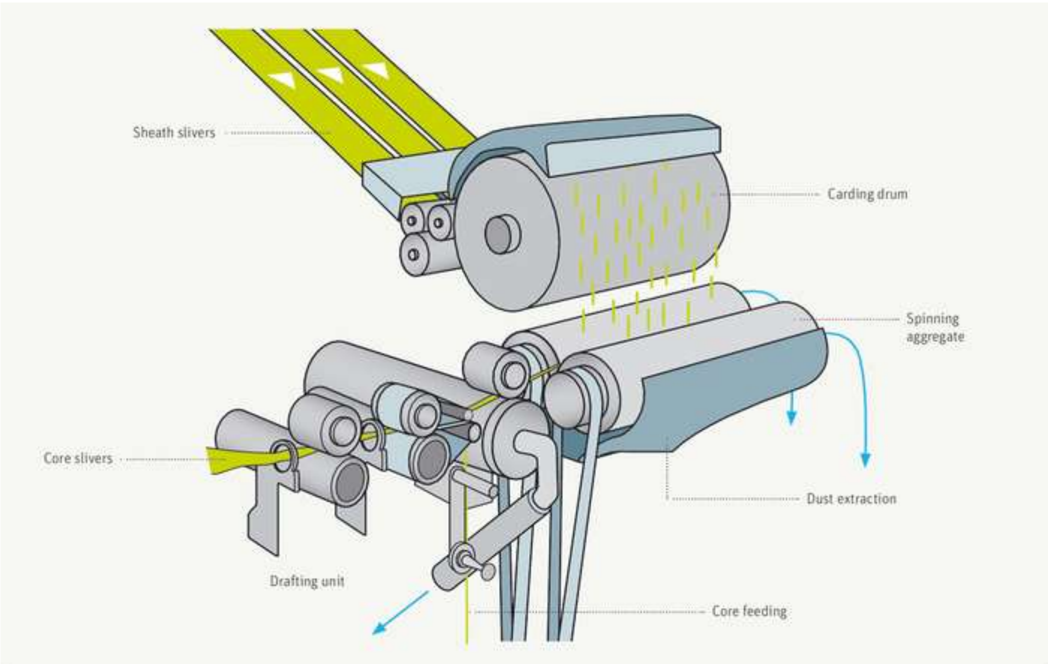


Figure 8. The Dref-3000 spinning unit (Rieter 2013)

Commercial Status

Commercial with very low adoption rate stage

References for Further Information

Ishtiaque (2003), Oxenham (2002)

3.3. Weaving

Compared to other textile subsectors, there are fewer emerging technologies for energy efficiency and emissions reduction in the weaving subsector. This is primarily because most of the new innovation in weaving is focused on production of new products, e.g. technical textiles or increasing the production speed and features of the existing technologies, which sometime could result in energy saving as a result of increased productivity. The subsection below describes one emerging alternative weaving technology: the multi-phase loom.

3.3.1. Multi-phase loom

Description

Single-phase weaving machines are close to their performance limits. Research on an alternative approach, multi-phase weft insertion, began in 1955, but the technology did not mature until 1990s. Sulzer demonstrated the M8300 multi-phase loom at ITMA' 1999. The M8300 was designed to be a single-warp machine and earmarked for mass production of standard fabrics without a multi-color mechanism. It has four sheds located in series around the circumference of a weaving central rotor. The warp threads are spread on the shed-holding element with the aid of warp positioners similar to the needle bars on knitting machines. A low-pressure blast of air through a weft channel formed by the shed-holding elements inserts the threads. Additional relay nozzles are placed within the shed-holding elements. The insertion rate is 1,200 m/min per shed with an overall rate of 4,800m/min for the machine. The combs positioned on the circumference of the weaving rotor beat up the weft. This loom is reported to have threefold greater productivity, lower specific energy consumption, lower process cost, and to be less noisy than single-phase machines (Matsuo 2008).

Since the introduction of the M8300, the range of yarns, yarn counts, and weaves it can produce has been expanded. Recently, the M8300 has been used exclusively for staple fiber yarns in the yarn count range tex 14.8 - 70 (Ne 8 - 40). Cotton, polyester, viscose, and blends of these yarns can be used as raw materials and have been used to produce fabrics in basic weaves – plain and three- and four-end twill. Filament yarns can now also be woven on the M8300. In the warp, smooth or texturized yarns can be used; in the weft, only texturized yarns can be used (Sulzer Textile 2002).

Energy/Environment/Cost/Other Benefits

The multi-phase loom has the following benefits compared to single-phase looms (Sulzer Textile 2002; Seyam 2000):

- Lower energy consumption for the same weaving output
- Highest production rate of any weaving machine
- Lower labor cost

Block Diagram or Photo

Figure 8. A multi-phase loom (Sulzer Textile 2002).

Commercial Status

Commercial with very low adoption rate stage

References for Further Information

Matsuo (2008), Sulzer Textile (2000, 2002)

3.4. Wet processing

3.4.1. Enzymatic treatments in textile wet processing

Enzymes are proteins that act as biocatalysts, activating and accelerating chemical reactions that would otherwise normally require more energy. The excellent substrate selectivity of enzymes allows more gentle process conditions compared to conventional forms of wet processing. Enzymes are present in bacteria, yeasts, and fungi (EIPPCB 2003).

Enzymes are used in textile finishing processes and are being studied for use specifically with natural fibers. Some state-of-the-art commercial enzymes include amylase for de-sizing starch and cellulose for bio-finishing. Enzymatic mixtures for cotton scouring, cotton bleaching, wool scouring, anti-felting, silk degumming, and flax softening are still in development (Nieminen et al. 2007).

Advantages of enzymatic processes compared to conventional techniques include lower processing temperatures and lower water consumption (because of reduced rinsing steps and cooling water use). Another benefit of enzymes is their biodegradability. Enzymes can also be used in catalytic amounts and recycled for reuse as biocatalysts (Schönberger and Schäfer 2003). Figure 10 show various types of enzymes that can be used in different wet processing steps.

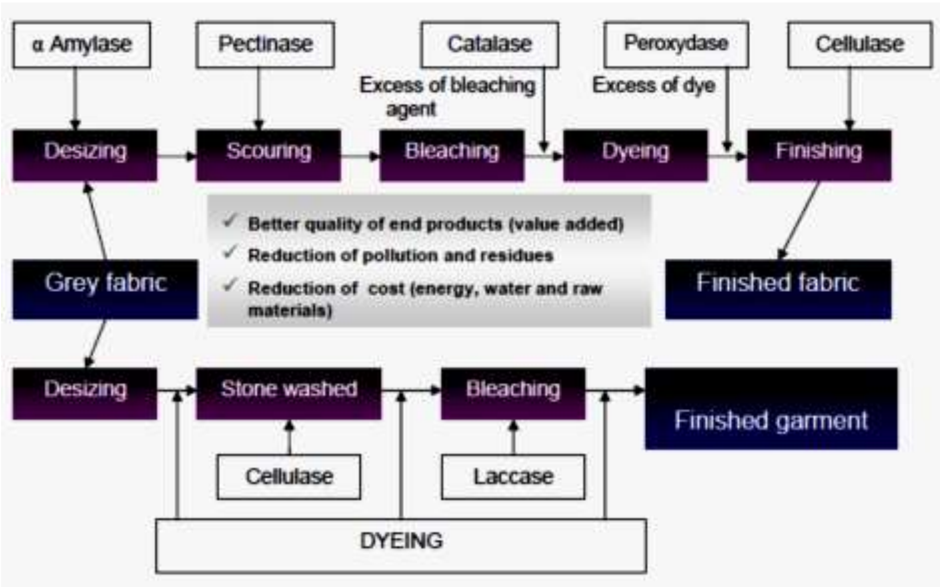


Figure 9. Utilization of enzymes in textile wet processing (LEITAT Technological Center, n. d.)

Some of the major applications of enzymes in textile wet processing are explained in more detail below.

3.4.1.1. Enzymatic scouring

Description

De-sizing, scouring with strong alkali, and bleaching are typical pre-treatment steps in cotton finishing mills. The scouring and bleaching steps are often combined. Scouring improves the wettability of cotton fibers by removing hydrophobic impurities, such as pectines and waxes. Enzymatic scouring, using enzymes in combination with surfactants (wetting agents and emulsifiers) and complexing agents, can replace the alkaline scouring process. Because enzyme-scoured textiles have better bleachability than textiles scoured by other methods, the quantities of bleaching chemicals and auxiliaries can be reduced for enzymatically scoured products (Schönberger and Schäfer 2003; Aly et al. 2004).

The enzymatic scouring process can be applied to cellulosic fibers and their blends, to woven and knitted goods, and in continuous or discontinuous processes. Enzymatic pre-treatment can also be combined with enzymatic de-sizing. Existing machines (jets, overflows, winches, pad batchers, pad steamers, and pad rollers) can be used with enzymatic scouring (Schönberger and Schäfer 2003).

Energy/Environment/Cost/Other Benefits

Enzymatic scouring has the following benefits compared to alkaline scouring (Schönberger and Schäfer 2003):

- 20 – 50 percent reduction in rinse water consumption
- No need for the sodium hydroxide used in common scouring
- 20 – 40 percent reduction in biochemical oxygen demand (BOD) and chemical oxygen demand (COD) loads in waste water
- Reduction in processing time

Block Diagram or Photo

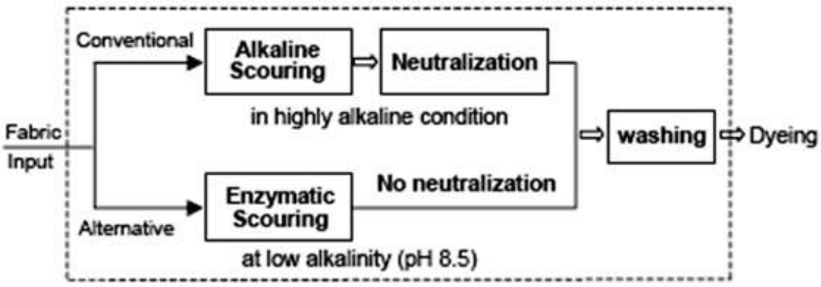


Figure 10. Flow diagram of enzymatic vs. alkaline scouring of cotton knits

Commercial Status

Commercial with very low adoption rate stage

References for Further Information

Schönberger and Schäfer (2003), Aly et al. (2004)

3.4.1.2. Enzymatic removal of residual hydrogen peroxide after bleaching

Description

To achieve reproducible bleaching results, a residual hydrogen peroxide content of 10-15 percent of the initial quantity needs to remain in yarns or fabrics after bleaching but must then be completely removed before the textile is dyed to prevent any change of shade when using dyestuffs that are sensitive to oxidation. Common peroxide-removal techniques use reducing agents and several rinsing steps. The main disadvantages of these conventional peroxide-removal techniques are high energy and water consumption and the use of sulphur-containing reducing agents (Schönberger and Schäfer 2003).

Special enzymes (peroxidases) catalyze the reduction of hydrogen peroxide to oxygen and water without causing side reactions with the substrate or dyestuffs. Enzymatic peroxide removal is possible in discontinuous, semi-continuous, and continuous processes and is applicable both in new and existing installations (Schönberger and Schäfer 2003). Heine and Höcker (1995) discuss enzymatic bleaching for wool and cotton.

Energy/Environment/Cost/Other Benefits

Enzymatic removal of residual post-bleaching hydrogen peroxide has the following benefits compared to conventional techniques (Schönberger and Schäfer 2003):

- Energy and water savings because the peroxidases have no negative influence on the downstream dyeing process, so liquor does not have to be drained following the enzyme treatment and prior to dyeing
- Complete biodegradability of peroxidases
- Reduction in rinse steps after peroxide bleaching (normally only one rinse with hot water is necessary after enzyme treatment)
- Avoided wastewater pollution from reducing agents used in conventional processes

Block Diagram or Photo

N.A.

Commercial Status

Commercial with very low adoption rate stage

References for Further Information

Schönberger and Schäfer (2003), Heine and Höcker (1995)

3.4.1.3. Enzymatic after-soaping in reactive dyeing

Description

When reactive dyes are used, soaping and rinsing steps are required afterward to remove non-fixed dyestuffs. Soaping and rinsing consume large amounts of energy, water, and chemicals. As an alternative, enzymatic techniques can remove non-fixed dyestuffs from fiber as well as from the exhausted dye bath. Usually, enzymatic compounds are applied during the fourth or fifth rinse step; applications for continuous processes and printing are currently being developed. Most reactive dyestuffs can also be decolorized with enzymes although a laboratory-scale test of this process is needed. This technique is used in several finishing mills in Germany as well as other parts of the world (Schönberger and Schäfer 2003).

Energy/Environment/Cost/Other Benefits

Enzymatic after-soaping in reactive dyeing has the following benefits compared to conventional techniques (Schönberger and Schäfer 2003):

- Reduced number of rinse steps
- Reduced detergent, water, and energy consumption

Block Diagram or Photo

N.A.

Commercial Status

Batch dyeing: Commercial with very low adoption rate stage

Continuous processes and printing: Development stage

References for Further Information

Schönberger and Schäfer (2003)

3.4.2. Ultrasonic treatments

Description

The frequency of ultrasonic waves is above 16 kilohertz (kHz), which is outside the audible range for human beings. To propagate, these waves require a medium with elastic properties. Ultrasonic waves cause the formation and collapse of bubbles (known as cavitation), which is generally considered to be responsible for most of the physical and chemical effects of ultrasound that are observed in solid/liquid or liquid/liquid systems (Vouters et al. 2004, Guglani 2008).

Ultrasonic waves can be created by mechanical transducers, piezoelectric transducers, or magnetic transducers. Ultrasound equipment consists of two main components: a generator and a converter or cleaning bath. The generator converts 50- to 60-Hertz (Hz) alternating current to high-frequency electrical energy, which is then fed to the transducer where it is transformed into mechanical vibration. The transducer system vibrates longitudinally, transmitting waves into a liquid medium. As these waves propagate, cavitation occurs (Guglani 2008).

During the past 20 years, experimental studies were performed on dyeing and washing of natural and man-made fibers assisted by ultrasound. In dyeing processes, the object is to transport or diffuse dyes or chemicals into a fiber (Vouters et al. 2004). Acoustic irradiation of the liquor results in a higher and more uniform concentration of dyestuff on the fiber surface, making it available for ready diffusion into the fiber interior (Ramachandran et al. 2008; EIPPCB 2003). Cavitation induced by ultrasound can accelerate these processes and produce the same results as existing techniques but at a lower temperature and lower dye and chemical concentrations (Vouters et al. 2004; Atav 2013).

Attempts have been made to analyze the effect of ultrasonic waves on dyeing using reactive and acid dyes as well as dye dispersants with almost all types of fibers. The ultrasonic method has been effectively utilized in various fabric preparation processes including de-sizing, scouring, bleaching, mercerization, as well as auxiliary processes such as washing (Ramachandran et al. 2008).

Vouters et al. (2004) and Ramachandran et al. (2008) review several studies on the use of ultrasonic waves in dyeing of polyamide, cotton, and nylon fabrics. Several studies have shown that ultrasonic treatment can speed up the washing process by two to three times or more for cotton, polyester, or wool fabrics (Vouters et al. 2004).

The lower cost of electronic components today compared to in the past makes the industrial application of ultrasound in dyeing and washing processes a feasible option. This technique can be implemented using existing machinery. The current restrictions on use of the ultrasound process in the textile industry are: 1) the kinetics of reaction because fixation times are limited by the nature of dyes and chemicals, 2) thermal limitations because, although an increase of temperature accelerates reactions, too high a temperature can damage textiles, and 3) mechanical limitations because textiles can be damaged if the pressure of the rollers used for hydro-extraction is too high (Vouters et al. 2004).

Energy/Environment/Cost/Other Benefits

Ultrasonic wet processing has the following benefits compared to conventional techniques (Schönberger and Schäfer 2003, Vouters et al. 2004, EIPPCB 2003):

- Energy savings resulting from lower process temperatures and shorter cycle times
- Reduced consumption of dyes and chemicals, which allows for a 20-30% reduction in the amount of effluent
- Water savings of around 20%
- Improvement in product quality
- Increased productivity because of shorter cycle times

Block Diagram or Photo

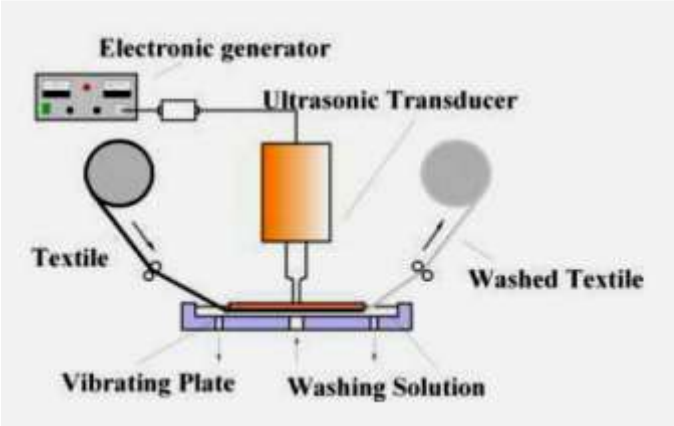


Figure 11. Schematic of ultrasonic textile washing machine (FLAiNOX 2011)

Commercial Status
Pilot stage

References for Further Information
Schönberger and Schäfer (2003), Vouters et al. (2004), EIPPCB (2003), INTEXUSA (2010)

3.4.3. Electron-beam treatment

Description
An electron beam (E-beam) or ray is generated by high voltage in an E-beam accelerator, which produces high-energy electrons (generally 300 kiloelectron-volts [keV] to 12 megaelectron-volts [MeV]). These electrons can be used to modify polymer materials through direct electron-to-electron interactions, which can create active sites such as radicals. Active sites can be formed on the polymer backbone by several methods, including plasma treatment, ultraviolet radiation, decomposition of chemical initiators, and high-energy radiation. Currently, the most common radiation types in industrial use are gamma and E-beam. Industrial E-beam accelerators with energies in the 150-300 keV range are used where low penetration is needed, such as for curing of surface coatings. E-beam machines have a high dose rate and therefore short processing times. E-beams have limited penetration compared with gamma radiation, and they use energy more efficiently because the energy can all be absorbed by the irradiated sample (Atav 2013).

E-beam irradiation is being increasingly utilized to modify the surfaces of polymer materials, such as fibers, textiles, and films. Electron beams cause free-radical-initiated polymerization reactions that can then be used for coating, lamination and for graft co-polymerization on textiles pre-coated with monomers or polymers. The advantage of E-beam irradiation over thermal curing is that it allows use of solvent-free formulations, which reduces volatile organic compound emissions during drying. The technique is already established in other sectors, so its implementation in the textile industry is foreseeable in the near future (EIPPCB 2003).

The effects of E-beam irradiation for treating the surface and improving the reactivity of natural fiber for bio-composites have been studied. E-beam irradiation can modify the surface structure and preserve the inner structure of natural fiber (Han and Choi 2010).

The textile chemical manufacturer Ciba has developed a series of dyes that contain polymerizable vinyl groups and are suitable for printing. E-beam irradiation can be used for fixation after printing with a paste containing a dye monomer and a specially selected cationic monomer. In lab tests, the target of 100% dye utilization was approached, and minimal washing off was required (Lewis 1999).

Energy/Environment/Cost/Other Benefits

E-beam textile surface treatment is reported to have the following benefits compared to conventional thermal curing (EIPPCB 2003; Han and Choi 2010; Schönberger and Schäfer 2003):

- Allows for use of solvent-free formulations, which reduces volatile organic compound emissions during drying
- Can be performed at room temperature, which saves energy
- Reduces processing time and increases productivity
- Estimated investment costs of € 0.5 - 0.75 million

Block Diagram or Photo

N/A

Commercial Status

Development stage

References for Further Information

EIPPCB (2003), Han and Choi (2010), Schönberger and Schäfer (2003), El-Naggar et al. (2003)

3.4.4. Use of ozone for bleaching cotton fabrics

Description

Conventional bleaching of cotton consumes large amounts of energy, water, and chemicals (hydrogen peroxide, etc.) and pollutes the water with chemical components and suspended solid particles. Ecological concerns have prompted a search for solutions to reduce the pollution resulting from the bleaching process. Utilizing ozone (O_3) to prepare cotton is one way to decrease these environmental impacts. O_3's oxidation potential is 2.07 electron-volts (eV), which is higher than that of the widely used bleaching agent, hydrogen peroxide (1.77 eV). O_3 is available in molecular form at an acidic pH (Eren and Ozturk 2011).

The use of O_3 for bleaching cotton is still under development. Various studies show that the whiteness of cotton fabric bleached with O_3 is comparable to that of conventionally bleached fabric but with greater decreases in degrees of polymerization. The O_3 process is environmentally preferable to peroxide bleaching because, when O_3 is used, there is no need for other harmful chemicals, much less water is required, and bleaching is achieved in a very short time at room temperature without the need for heating or cooling energy (Perincek et al. 2007; Prabaharan et al. 2000).

The equipment used for O_3 bleaching has three components: the ozone generator, the applicator, and the ozone destroyer (Rane and Jadhav n. d.). The input for the generator is oxygen from a pressurized cylinder. The generator supplies the required concentration of O_3-oxygen mixture to the applicator, a glass cylindrical tube with a diffuser at the bottom (Rane and Jadhav, n. d.). O_3 is produced by subjecting the 20% of oxygen present in air to pressure swing adsorption and raising its concentration to 90%; then, plasma discharge is used to generate O_3 (Ozone Bleach Association 2013a).

In a study by Eren and Ozturk (2011), O_3 was used in to prepare fibers for de-sized and scoured 100%-cotton fabrics. The study found that hydrogen peroxide-bleached, 60-min ozonated, and 90-min ozonated samples all had a similar degree of whiteness. Loss in strength after prolonged ozonation was negligible (Eren and Ozturk 2011).

Energy/Environment/Cost/Other Benefits

Use of O_3 gas for cotton bleaching is reported to have the following benefits compared to conventional hydrogen peroxide bleaching (Perincek et al. 2007; Eren and Ozturk 2011; Ozone Bleach Association 2013b):

- Energy savings because bleaching is achieved at room temperature without requiring any heating or cooling energy
- Reduced CO_2 emissions by up to 50%
- Substantial water savings
- No need for harmful chemicals
- Increased productivity because bleaching is done in a very short time

Block Diagram or Photo

N/A

Commercial Status

Development stage

References for Further Information

Perincek et al. (2007), Eren and Ozturk (2011), Ozone Bleach Association (2013a,b)

3.4.5. Advanced cotton fiber pre-treatment technology to increase dye receptivity

Description

Altering the molecular structure of cotton fiber can increase its dye receptivity so that smaller amounts of dye and no salt and alkali are required. The ColorZen cationic process is based on this pre-treatment concept (ColorZen 2012).

Because the only auxiliary dye chemical used in the ColorZen process is a small amount of wetting agent, overall chemical use is reduced by 95 percent compared to traditional dye processes. If the ColorZen dyebath is recycled for reuse in a subsequent dyeing process, the wetting agent in the bath also can be reused. The initial cost of the process is slightly higher than that of conventional cotton pre-treatment processes, but no capital investment is required for new equipment. In the longer term, savings from reduced energy, water, dye, and chemical usage can compensate for the extra initial cost. The process can be used on any 100%-cotton fabric (knitted or woven). One possible exception is denim because of its indigo-dyed warp. There are concerns about variations in dye fixation with this process, which the manufacturer is working to improve (Textile World 2012a). ColorZen opened its first processing facility in China (Textile World 2012b).

Energy/Environment/Cost/Other Benefits

The ColorZen cotton fiber pre-treatment technology is reported to have the following benefits compared to conventional dyeing of non-treated fibers (ColorZen 2012; Textile World 2012b):

- 75% lower energy consumption because color is applied at lower dyeing temperatures
- 90% less water consumption because the dye bath is only filled twice, compared to six or more times with conventional dyeing.
- Reduced amounts of dyestuff used, and no salt and alkali required for dye fixation
- Lower cost for treating dye wastewater
- Higher productivity because the dye process is around three times faster

Block Diagram or Photo

N/A

Commercial Status

Pilot stage

References for Further Information

ColorZen (2012), Textile World (2012a,b)

3.4.6. Use of supercritical carbon dioxide in dyeing

Description

All materials above critical temperatures and pressures are supercritical fluids. Only one phase exists in the supercritical region, which is neither liquid nor gas but has properties of both. The density and the dissolvability of supercritical fluids are similar to those of liquids, but the viscosity and the diffusion properties are similar to those of gases. When materials expand or are cooled below the critical temperature, their solvent ability is lost, so the pulverized or liquefied solute falls out (Tušek et al. 2000; Atav 2013).

CO_2 is frequently used as a solvent because of its non-toxic, non-corrosive, and non-hazardous nature as well as the fact that it is produced commercially and can be transported easily. It is relatively easy to achieve critical temperature and pressure for CO_2 compared to other gases (Ramachandran et al. 2008).

Using supercritical CO_2 as a dye medium is a promising emerging process. The key property of supercritical CO_2, that makes dyeing possible is its ability to dissolve hydrophobic substances, including dye dispersants. The supercritical fluid performs two functions in the dyeing process: it heats the substrate and transports the dyes**.** The process can be controlled by temperature and pressure (Tušek et al. 2000).

The dissolved dyestuff that diffuses into the boundary layers of the supercritical fluid is absorbed and diffuses into the fibers. The state of the dyestuff in a super critical solution can be described as gaseous (Ramachandran et al. 2008). The supercritical CO_2 dyeing process uses almost no water, and drying is not required because, at the end of the process, CO is released in the gaseous state. Up to 90% of the CO_2 can be recycled easily after precipitation of the extracted matter in a separator (Bach et al. 2002).

CO_2 dyeing of polyester (the most widely used textile fiber) and polypropylene fiber has already been developed on an industrial scale; however, the application of this technique on wool, polyacrylate, and cotton is still problematic because of the polar nature of the dyestuffs used to color these fibers. Dyeing of polyester in supercritical CO_2 should be performed at a pressure above 180 bar and a temperature above 70°C (Tušek et al. 2000).

For polyester and polypropylene dyeing, dye uptake and fastness properties are very similar to those in water dyeing. However, some precautions need to be taken. For example, excess dye dissolved in the dye medium must be extracted with fresh supercritical CO_2 at the end of the dyeing cycle. Also, hydrophobic preparation agents should be extracted before dyeing because of their solubility in supercritical CO_2. They are extracted from the fiber during the dyeing process and then precipitate as oily droplets at the end of the process (EIPPCB 2003).

Some of the auxiliary substances in conventional dye formulations (e.g., dispersing agents, oils, and anti-dust materials) strongly influence the dye release in supercritical CO_2. Therefore, only dyes formulated with certain special additives should be used in supercritical CO_2 dyeing (Schönberger and Schäfer 2003).

Tušek et al. (2000) investigated the effect of pressure and temperature on dyeing of polyester in supercritical CO_2, with one dye as well as with mixtures of two or three dyes. They found that the amount of dye absorbed by the fabric increases with rising temperature because of the accelerated motion of molecular chains and the formation of free volume in the fiber, which is important for dye diffusion. The change in pressure does not significantly alter the amount of fixed dye when mixtures of dyes are used, but the ratio among the dyes is changed (Tušek et al. 2000).

A disadvantage of this technology is the substantial investment cost for the equipment. This is a significant drawback because polyester textiles are normally low-price products (EIPPCB 2003).

The Dutch company DyeCoo Textile Systems produced the first industrial dyeing machines that use super critical CO_2. The polyester textile producer Tong Siang Co. Ltd in Thailand is the first textile mill to implement a commercial-scale supercritical fluid CO_2 machine. Currently, the process is used only for dyeing of scoured polyester fabric in batches of 100-150 kg although DyeCoo and its partners are developing reactive dyes for cellulosic fibers (Textile machinery 2010).

Energy/Environment/Cost/Other Benefits

Supercritical CO_2 dyeing has the following benefits compared to conventional dyeing (EIPPCB 2003; Schönberger and Schäfer 2003; Bach et al. 2002):

- Almost zero water consumption
- Zero off-gas emissions (CO_2 can be recycled)
- No drying step necessary after dyeing, which saves significant energy
- Leveling and dispersing agents not needed, or, in some cases, used only in very small amounts
- Recyclability of dyestuff residues

Block Diagram or Photo

Figure 12. DyeCoo's supercritical CO_2 dyeing machines (DyeCoo 2012)

Commercial Status

Pilot stage

References for Further Information

EIPPCB (2003), Schönberger and Schäfer (2003), Bach et al. (2002), Tušek et al. (2000), DyeCoo (2012)

3.4.7. Electrochemical dyeing

Description

Vat dyes (including indigo) and sulfur dyes account for a large part of the dyestuff market for cellulosic fibers. In addition to their well-known advantages, vat and sulfur dyes have a complicated application procedure, involving reduction and oxidization steps (Schönberger and Schäfer 2003).

Conventional reducing agents used for the reduction of dyestuffs result in non-regenerable oxidized byproducts that remain in the dyebath. Used dyebaths cannot be recycled because the reducing power of these chemicals cannot be regained. Disposal of these dyebaths and associated wastewater causes a variety of environmental problems, e.g., introducing into the environment sulphite and sulphate from the use of dithionite, sulphides from sulphur dyes, and causing a high COD because of the presence of organic reducing agents (Das et al. 2012).

An attractive alternative technique is to reduce and oxidize dyes using electrochemical methods. In direct electrolysis, the dye is reduced at the surface of the cathode (EIPPCB 2003). In practice, the dyestuff is partially reduced using a conventional reducing agent; then, a complete dye reduction is achieved using the electrochemical process. This improves the stability of the reduced dye (Das et al. 2012).

In indirect electrochemical dyeing, the dye is not directly reduced at the electrode surface. Rather, a reducing agent (regenerable Fe_2^+/Fe_3^+) that reduces the dye in the conventional manner is added. This agent is oxidized after dye reduction and subsequently reduced at the cathode surface so that it becomes available again for reducing dyes. This cycle repeats continuously during the dyeing operation. In electrochemistry, an agent that undergoes both reduction and oxidation cycles (a reversible redox system) is called a mediator (Das et al. 2012).

Issues that must be addressed in scaling-up of the indirect electrochemical reduction process are (Kulandainathan et al. 2007a):

- The actual reduction of the dye should be carried out separately in an electrochemical cell; the reduced dye should then be circulated separately into a conventional dyeing unit, e.g., a jigger.
- To keep the dye in the reduced form, it is necessary to reduce the oxidized mediator at the cathode. This is possible only when there is a continuous circulation of the dye liquor from the dyeing equipment to the electrochemical cell.
- The design of the cell should be such that the cathode has the maximum surface area available for reducing the mediator.
- Three-dimensional electrodes with large surface area that occupy a small space in the electrochemical cell should be designed. This kind of cell will have the advantage of reducing dye using a minimum volume of mediator.
- The cell should have a minimum area of separator (a separator is a semi-permeable membrane that isolates anolyte from catholyte) to minimize separator cost and prevent the re-oxidization processes from taking place because of bleeding of the separator and diffusion of oxygen. Re-oxidization at the separator can cause a chemical short-circuit, requiring enlargement of the cathode area.

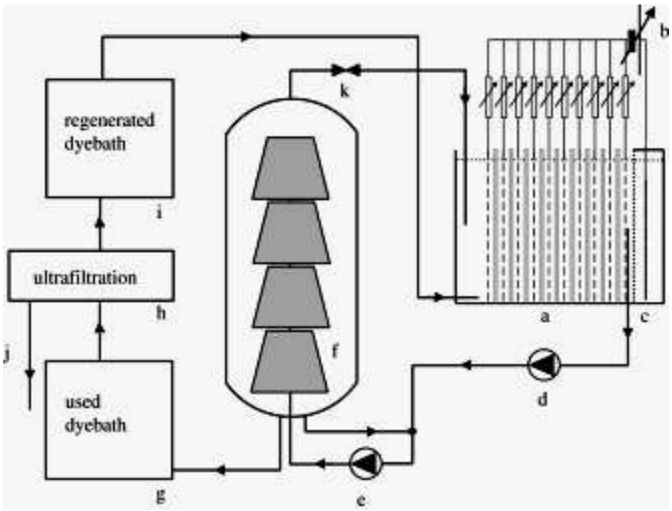
Electrochemically reduced vat dyes have been tested on a laboratory scale in dyeing experiments; the results of different reduction conditions are discussed by Kulandainathan et al. (2007b), Bechtold and Turcanu (2009), Roessler et al. (2004), and Roessler et al. (2002).

Austria-based Getzner Textil signed a cooperation agreement in 2001 with the Technology Team Electrochemistry Textile (TET), headed by DyStar Textilfarben, Germany. Under the agreement, Getzner was the first company to pilot DyStar's patented electrochemical dyeing process. Getzner used the technology to vat-dye yarn on a package-dyeing unit (Textile World 2002).

Energy/Environment/Cost/Other Benefits
Electrochemical dyeing is reported to have the following benefits compared to conventional dyeing (Schönberger and Schäfer 2003; Das et al. 2012):

- Recycling of the mediator system and dyeing liquors, which significantly reduces chemical and water consumption
- No toxic sulphates and sulphites in effluent, so no adverse effect on aquatic life
- Lower concentration of chemicals
- Considerably reduced wastewater discharges, which saves energy at wastewater treatment plants
- Avoidance of odor and other problems caused by conventional sulfur-containing reducing agents

Block Diagram or Photo



a. cathode compartment with three-dimensional flow through cathodes, b. power supply, c. anode compartment, d. pump for circulating cell-dyeing materials, e. circulation pump of dyeing materials, f. dyebath with yarn cones, g. dyebath tank, h. ultra-filtration unit, i. regenerated dyebath storage tank, j. drain for residue containing dyestuff, k. throttle to adjust static pressure in apparatus.

Figure 13. Schematic of electrochemical package dyeing apparatus (Bechtold and Turcanu 2009)

Commercial Status
Development stage

References for Further Information
Schönberger and Schäfer (2003), Das et al. (2012), Kulandainathan et al. (2007b), Bechtold and Turcanu (2009), Roessler and Crettenand (2004), Roessler et al. (2002)

3.4.8. Ink-jet printing (Digital printing)

Description

Ink-jet or digital printing of textiles emerged in the 1990s for prototyping and printing small batches of fabric for niche market products. This technology has developed dramatically since then (Tyler 2005). In simplified terms, ink jet printing of textiles is a contactless technology that works similarly to an office printer. It enables quick response and a great deal of flexibility especially in patterning. Color type and position on the textile are recorded digitally and supplied to the printing system. The transformation of the sample on the substrate takes place via innumerable ink drops pressed out of printing nozzles. Several drops of one color generate each "dot" of the dots per inch (dpi) that make up the digital image. A raster program puts these drops one upon another or side by side using an organizing principle based on base shade, tinctorial power, and pattern. The two types of ink-jet printing for textiles are continuous flow and drop on demand, shown in Figures 15 and 16 (Schönberger and Schäfer 2003; Matsuo 2008).

Most fabrics need pre-treatment before digital printing; the extent of pre-treatment depends on the inks to be used. Pre-treatment chemicals inhibit dye from migrating once it has landed on the substrate and can also be used to control pH. Digitally printed inks have low viscosity to allow flow through the print head; for comparison, screen-printing pastes have a viscosity of about 5,000 mega-Pascals (mPas) whereas ink jet fluids have a much lower viscosity of 3 to 15 mPas. This low viscosity creates problems when the ink reaches the textile substrate because fluid moves away from the target by wicking. Therefore, the textile substrate has to be prepared by adding a thickener that provides enhanced absorbency to prevent wicking. In some cases, the thickener can cause the textile to develop a hard handle. If this adversely affects its end use, a scouring process is required after printing to remove the thickener (as well as unfixed dye). In other cases, there may be no adverse handle effects, eliminating the need for scouring (Tyler 2005).

Every printed fabric (except those used for transitory purposes such as photo shoots) needs post-treatment to complete the printing process. Steaming opens up the fabric's fibers, so the dyes can be fixed. Generally, steaming for a short time (8–10 minutes at 102 ºC) is considered to produce prints with weak colors; strong, vibrant colors require steaming for at least 17 minutes. Often, washing is required because the uptake of acid and reactive dye is never 100%; this creates particular requirements for processing small batches. For commercial reasons, post-treatments are not done unless the end use requires them. So, for example, printed fabrics intended for photo shoots are not even fixed. Pre-treated fabrics are not scoured unless necessary to remove impurities (Tyler 2005).

A representative advanced printing machine exhibited at ITMA 2007 can dye 80 square meters per hour (m^2/h) of 320-cm-wide fabric using 16 colors at 600 dpi. The printing process can be used for reactive, acid, dispersant, and pigment dyeing. In March 2008, a machine with an operation speed of 400 m^2/h using eight colors at 600 dpi was presented by a Japanese company.. Improvement in production efficiency has made ink-jet printing a favorable technique. Advantages of digital printing include: images generated by computer-aided design can be precisely and directly transferred to fabric, and filing and indexing of image data are very easy, allowing ink-jet printing to respond more quickly than conventional printing methods to market demands (Matsuo 2008; King 2009).

Energy/Environment/Cost/Other Benefits

Ink-jet textile printing has the following benefits compared to conventional printing (Schönberger and Schäfer 2003; Tyler 2005):

- Reduced energy consumption
- Reduced water consumption (washing of printing equipment is not necessary)
- Indirect printing method (no requirements for printing screens, etc.)
- No (or smaller amount of) thickeners required
- Higher fixation rate
- Only a small dyestuff palette is needed
- Almost no dyestuff surplus, which reduces load on wastewater treatment plant
- Flexibility in production and patterns

Block Diagram or Photo

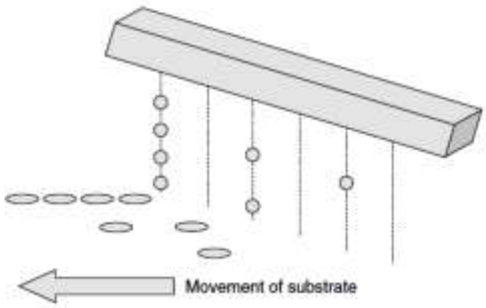


Figure 14. Drop-on-demand concept (a drop of ink is produced in reponse to a signal to fire the nozzle) (Tyler 2005)

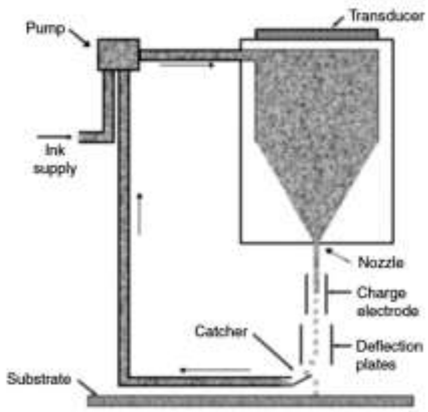


Figure 15. Continuous ink-jet concept (drops of ink are produced continuously and either fall on the substrate or are recycled) (Tyler 2005)

Commercial Status

Commercial with very low adoption rate stage

References for Further Information

Schönberger and Schäfer (2003), Matsuo (2008), Tyler (2005)

3.4.9. Plasma technology in textile wet processing

Description

Plasma can be characterized as a mixture of partially ionized gases; that is, plasma contains gases that are decomposed as a result of high induced electrical energy. Atoms, radicals, ions, and electrons can be found in plasma. Low-temperature plasmas normally used for surface treatment contain electrons with high kinetic energy compared to the gas temperature. The electrons in the plasma can cleave covalent chemical bonds. Therefore, physical and chemical modification of the surfaces of various substrates is possible with plasma technology. Two types of plasma are generally used: corona and low-pressure (EIPPCB 2003).

Plasma treatment can be performed on natural as well as on man-made fibers. Plasma treatment for apparel and industrial textiles includes the following possible applications: pre-treatment (de-greasing of wool, de-sizing), changes in wettability (hydrophilic, hydrophobic properties), pre-treatment for dyeing and printing (increasing dyestuff affinity, improving leveling properties, increasing bath exhaustion), and shrinkage and anti-felt finishing for wool (most studied and very promising; plasma treatment causes less degradation of the wool fiber than other processes and avoids the presence of absorbable organic halides in the wastewater). Additional applications of plasma treatment in the textile industry include: sterilization (anti-bacterial finish), improvement of textile stability in response to aggressive gases and fluids, and improvement of fiber matrix adhesion (for use in composites) (Schönberger and Schäfer 2003).

The structure of fibers and the structure and construction of yarn and fabrics play major roles in determining the efficiency of plasma processing. Plasma processing is affected by the presence of impurities in raw fibers and of additives in yarn and fabrics (Nasadil and Benesovsky 2008). Nasadil and Benesovsky (2008) investigated the possibilities for plasma pre-treatment in different forms of textile wet processing. Developments in plasma treatment for wool have been reviewed by Kan and Yuen (2007). Some of the effects of plasma treatment on dyeability of proteinous fibers are summarized in Atav (2013).

A plasma-treated wool surface has favorable dye uptake, finish, and adhesion properties. Because plasma-treated woolen materials have better dye pick-up, more color value can be achieved with these wool fabrics than with untreated fabrics, for the same strength of dyestuff. The plasma treatment enhances the surface tension of the wool, which in turn increases the fabric’s adhesion property during coating. The plasma treatment also significantly improves the wool’s shrink-proofing. Because it is a physical process, plasma treatment does not involve any industrial effluent, so it eliminates the pollution associated with chemical treatments (Kan and Yuen 2007).

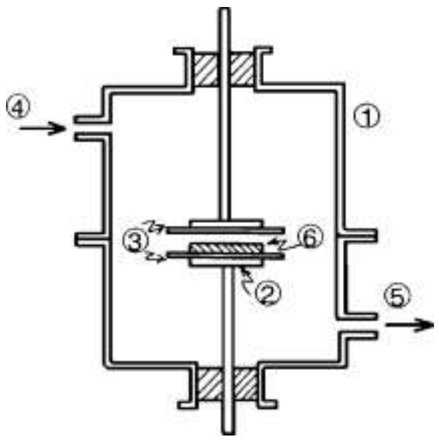
Although industrial-scale continuous plasma treatment is in the investigation stage, atmospheric pressure plasma treatment equipment can be inserted "inside" existing textile-processing machines so that the plasma treatment can be carried out in line immediately before the traditional process, as an alternative to continuous plasma treatment (Kan and Yuen 2007). Of the two types of plasma, corona technology has the advantages of easy construction and handling. One fundamental reason why low-pressure plasma technology is not realized on a commercial scale is that a vacuum is needed, so textiles that will receive this treatment have to be dried carefully. The high volume of fabrics that is treated, humidity of the textiles (especially in case of natural fibers), and presence of residual auxiliaries lead to high operating costs of the plasma treatment; thus, the humidity and residual auxiliaries should be reduced to minimum before the plasma treatment. (Schönberger and Schäfer 2003).

Energy/Environment/Cost/Other Benefits

Plasma treatment has the following benefits compared to conventional treatment techniques (Schönberger and Schäfer 2003; EIPPCB 2003):

- Low application temperature, which saves energy
- No (or a small amount of) water and solvents required
- Avoidance of drying steps after plasma finishing, which saves energy
- Considerable savings of dyestuff and finishing auxiliaries
- Shorter treatment time
- Considerable improvement in wool prints

Block Diagram or Photo



(1) glass jar, (2) brass electrode, (3) dielectric layer (polyamide), (4) gas inlet, (5) gas outlet,(6) specimen for treatment

Figure 16. Apparatus for atmospheric low-temperature plasma treatment (Kan and Yuen 2007)

Commercial Status

Pilot stage

References for Further Information

Kan and Yuen (2007), Atav (2013)

3.4.10. Foam technology for textile finishing

Description

Wet processing of textile materials consumes a large amount of energy and accounts for a major share of the energy used in the textile industry in many countries. Most of this energy is consumed in heating and evaporation of water from fibers. Also, a large amount of water is consumed in textile wet-processing. Foam finishing is an alternative method in which the liquor is diluted using air instead of the water that is normally used to apply chemicals to textile materials. Because most of the water that is normally used is replaced by air in foam finishing, energy requirements in the drying processes are reduced along with water consumption and wastewater disposal (Ramachandran et al. 2008). Foam technology also offers a solution to a basic problem encountered with other low-add-on topical and expression systems: the difficulty of distributing a relatively small quantity of liquor uniformly over a large surface of fabric (Elbadawi and Pearson 2003).

Foam is a colloidal system comprised of a mass of gas bubbles dispersed in a liquid continuum. Foam can be generated mechanically by air blowing or excess agitation, chemically by introduction of foaming agents, or by a combination of these methods. The relative proportions of air and liquid phases in the foam are designated by the blow ratio. Foam stability, density, and diameter are important parameters that need constant attention. Systems commonly used in foam applications are: horizontal padders, kiss roller coating, knife-over-roller coating, knife on air, and slot applicators. After foam is applied to fabrics, it can be destroyed by conventional padding, vacuum application, or a combination of both (Ramachandran et al. 2008).

Foam can be used in fabric preparation, dyeing and printing, durable press finishing, softening, soil-release finishing, mercerizing, and various types of finishes (water- and oil-repellant, fire retardant, anti-static, etc.). The foam can be applied on one or both sides of the fabrics (Ramachandran et al. 2008). Foam finishing systems can be retrofitted on most existing equipment (Gaston Systems 2012).

Energy/Environment/Cost/Other Benefits

Foam finishing has the following benefits compared to conventional finishing techniques (Ramachandran et al. 2008; Elbadawi and Pearson 2003; MEOEA 1999):

- Up to 80% reduction in water consumption
- Up to 65% reduction in energy consumption
- Reduced wastewater discharge
- Increased production speed (stenter speed can be increased for drying, or stenter and pre-drying can be eliminated)
- Reduced chemical add-ons
- Improved finished-fabric physical properties
- Payback period as short as six months to two years

Block Diagram or Photo

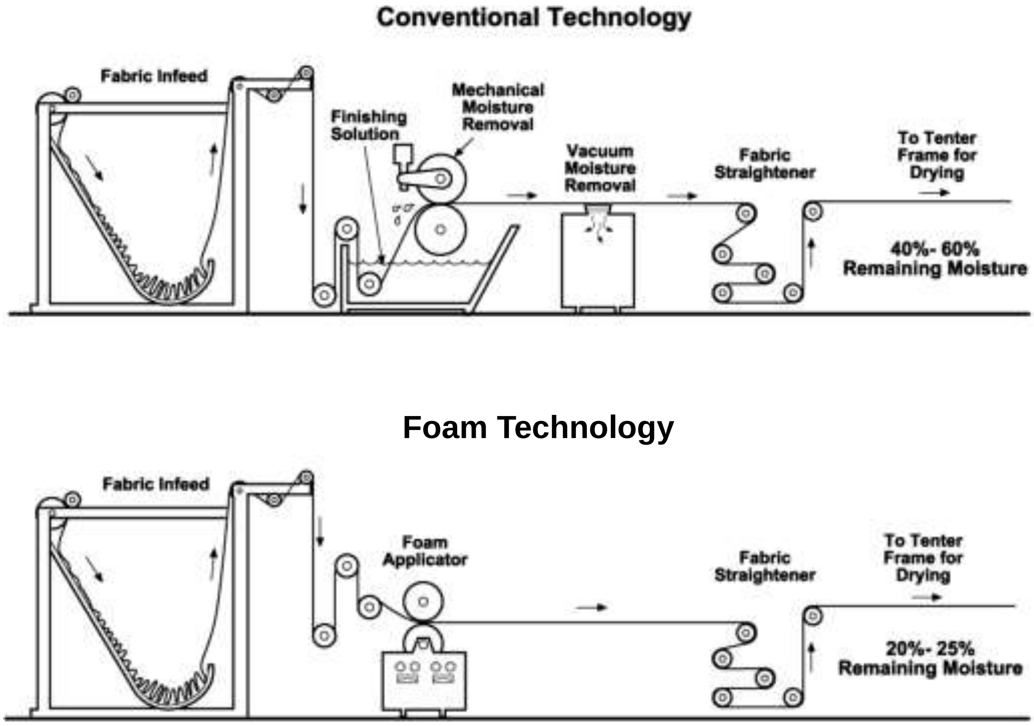


Figure 17. Comparison of conventional and foam technology used in Brittany dyeing and printing plant (MEOEA 1999)

Commercial Status

Commercial with very low adoption rate stage

References for Further Information

Ramachandran et al. (2008), Elbadawi and Pearson (2003)

3.4.11. Microwave energy in textile wet processing

Description

Microwaves are electromagnetic waves with frequencies ranging from 1,000 megahertz (MHz) to10,00,000 MHz (Guglani 2008). Microwave energy has found a number of applications in industrial processes in various sectors where it is used as an alternative to conventional heating techniques because it provides fast, uniform, and effective heating by penetrating the particles in matter and enabling their simultaneous heating. Advantages of microwave energy include: shorter application times, quicker heating and drying, ability to easily change process time to heat different volumes of material, and energy conservation (Büyükakıncı 2012).

In the textile industry, microwave energy has been tested in heating, drying, condensation, dyeing, pressing, finishing, and modifying the surface of materials. The first attempt to use microwaves in the textile finishing process was during the 1970s when cellulose fabrics were treated with durable press finishing agents and cured in a microwave oven (Katovic et al.

2005).

An example of the use of microwaves in textile production is microwave dyeing, which takes into account the dielectric and thermal properties of the process. The dielectric property refers to the intrinsic electrical properties that affect the dyeing by dipolar rotation of the dye; these electrical properties influence the microwave field on the dipoles. An aqueous dye solution has two polar components. The high-frequency microwave field oscillating at 2,450 MHz influences the vibration energy in the water and dye molecules. The heating mechanism is ionic conduction, which is a type of resistance heating. The acceleration of the ions through the dye solution causes dye molecules to collide with the molecules of the fiber. A mordant affects the penetration of the dye, including the depth of penetration into the fabric (Guglani 2008).

Safety measures must be developed prior to using microwave energy on a large scale because excessive exposure to microwave radiation is hazardous (Katović 2011). Büyükakıncı (2012), Atav (2013), and Katovic (2010) review various application of microwave energy in textile wet processing.

Energy/Environment/Cost/Other Benefits

Microwave heating in textile wet processing has the following benefits compared to conventional heating techniques (Büyükakıncı 2012; Bhat et al. 2009; Katovic et al. 2005):

- Lower energy use
- No direct air pollution (indirect air pollution from electricity use is still less than that resulting from conventional heating)
- Localized heating, which reduces energy waste in the heating process
- Faster heating, which increases productivity and reduces energy use
- More uniform heating

Block Diagram or Photo

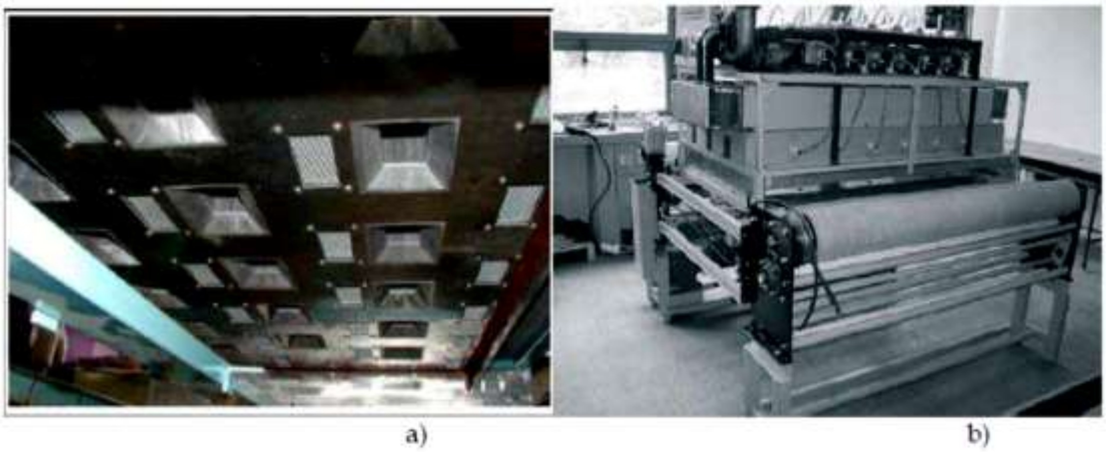


Figure 18. a) Interior of the microwave drying machine, b) Prototype of semi-industrial microwave drying machine (Katovic 2010)

Commercial Status
Development stage

References for Further Information
Büyükakıncı (2012), Bhat et al. (2009), Katovic et al. (2010 and 2005)

3.4.12. Alternative textile auxiliaries

Description
A significant trend in textile manufacturing is toward environmentally friendly textile products that use less energy and water and fewer toxic chemicals. This trend is being driven in part by government restrictions on chemical use. New textile chemicals need to provide the desired performance with a minimum of pollution. Recent developments to reduce the environmental impact of textile auxiliaries are reviewed below (Hauser 2006).

The bio-scouring process utilizes several enzymes to catalyze hydrolysis of warp sizes and impurities in cotton.

Specialty surfactants have been developed that claim to allow combining of de-sizing and scouring without the use of amylase; these surfactants can disperse and remove starch sizing in alkaline solutions.

Incorporating a biodegradable stabilizer into a hydrogen peroxide bleach bath reduces the load on wastewater treatment facilities.

Alkyl phenol ethoxylates that are used in textile processes are excellent surfactants but biodegrade to materials that are toxic to aquatic life, so many textile chemicals have been reformulated to remove alkyl phenol products.

Use of peroxide bleach activators can reduce the time and temperature associated with hydrogen peroxide bleaching. Two such activators are tetraacetylethylenediamine and nonanoyloxy-benzene sulfonate, which have been adopted on a limited basis in the textile industry (Hauser 2006) .

Another technology under development is the use of cationizing agents on cotton prior to dyeing. Cationic cotton utilizes dye better and has higher color values than cotton not pre-treated in this manner. In addition, the strong dye-fiber interactions resulting from cationizing allow dyeing with no added electrolytes and minimal rinsing and after-washing (Hauser 2006).

Use of polyasparginic acid as a substitute for conventional dispersing and complexing agents is under study. This product is biodegradable and does not have potential to remobilize toxic heavy metals. Polycarbonic acids can be used as an alternative to N-methylol-based cross-linking agents, which are responsible for formaldehyde emissions (EIPPCB 2003;

(Schönberger and Schäfer 2003).

Recent softener advancements include a silicone oil that is self-emulsifiable and 96% active. This product reduces shipping and inventory costs and can be made into a useful emulsion in the mix room. A 100% active cationic non-silicone softener is available that can be added directly to dyeing machines without prior dilution or emulsification (Hauser 2006).

Energy/Environment/Cost/Other Benefits
One or more of the following benefits can be achieved by alternative textile auxiliaries compared to conventional auxiliaries:

- Reduced energy and water consumption
- Reduced environmental pollution
- Higher productivity
- Reduced load on wastewater treatment facilities

Block Diagram or Photo
N.A.

Commercial Status
Various stages of commercialization depending on the auxiliary

References for Further Information
Hauser (2006), Schönberger and Schäfer (2003)

3.5. Sensor and control technologies

3.5.1. Fuzzy logic and other expert systems in the textile industry

Description:
Process reliability can be improved significantly with the use of expert systems, which are essentially computer programs that either recommend or make decisions based on knowledge collected from experts in the field (rule-based systems) or databases of previous formulations (case-based systems) (Shim 2009).

Textile wet processing involves the interaction of a large number of variables whose exact relation to product properties has yet to be established conclusively. This is because of the high degree of variability in raw materials, the complexity of multi-stage processing, and a lack of precise control of process parameters, among other reasons (Shim 2009).

Expert systems can integrate the perspectives of individual disciplines (e.g., pre-treatment, dyeing, finishing) into a framework for decision making for textile production. Expert systems have been employed in many fields within the textile industry. Some of these applications are reviewed below. A more comprehensive review of expert systems in the textile industry can be found in Shim (2009).

Expert systems are used in textile production (Shim 2009; Shamey and Hussain 2003) to:

- Predict the characteristics of a yarn according to those of the raw material, or to select the raw material to produce yarn that has specific characteristics
- Diagnose faults in a filament yarn spinning machine
- Design industrial fabrics and made-to-measure clothing
- Help technicians with machines that exhibit excessive warp and weft stops, quality problems, and mechanical and electrical malfunctions
- Reduce diagnostic time and trial-and-error procedures
- Schedule production

In dyeing and finishing, expert systems are used for:

- Bleaching cotton fabrics
- Determining dyeing recipes
- Optimizing dyeing processes
- Executing textile finishing recipes and monitoring performance
- Selecting fluorescent whiteners
- Matching color and optimizing lab-to-bulk reproducibility
- Managing the dyeing control system

Fuzzy logic is based on self-learning software systems, which auto-enlarges their knowledge using algorithms (EIPPCB 2003). A fuzzy logic system is useful when a situation has too many variables to account for all of them with complete precision. The fuzzy logic general inference process proceeds in three (or four) steps as shown in Figure 20 (Shim 2009).

Major areas of fuzzy logic application in the textile industry include classification, grading, diagnosis, planning, and control. The main strength of fuzzy logic is that it can address uncertainty and imprecision in decision-making processes, for example cotton color classification. A fuzzy inference system that uses fuzzy logic to classify cotton colors has been developed; the preliminary results show it is effective in reducing machine-classer disagreements about color grading, and that it shows good consistency over multiple years of cotton color data (Shamey and Hussain 2003). Fuzzy logic also can be used to control the sizing process and the condensation reaction among cross-linking agents (EIPPCB 2003; Shim 2009).

Heriot-Watt University developed a diagnostic fuzzy logic system for the dyeing of cotton material. The system comprises 4,786 rules and is capable of diagnosing about 132 faults in the pre-treatment and dyeing of cotton in woven, knitted, and yarn package form using direct, reactive, vat, sulphur and azoic dyes. The system also suggests corrective measures (Shim 2009). Another example of the use of fuzzy logic is for speed control of looms. A computer program has been developed to simulate the speed control of weaving machines using fuzzy logic. The program is based on an assessment of the weaver's load, the running behavior of the weaving machine, the speed range, and the shutdown frequency (Shamey and Hussain 2003).

Other applications of fuzzy logic in textiles include: determination of the handle of fabric with fuzzy cluster analysis, identification of various trash types (non-lint material/foreign matter) in cotton, regulation of spinning machine operation to optimize production, improvement of draw-frame regulation, and representation of fabric by a computer-aided design system in the dobby weaving sector (Shamey and Hussain 2003).

The main limitation in the implementation of these expert systems in the textile industry is often the lack of a reliable database (EIPPCB 2003).

Energy/Environment/Cost/Other Benefits

Fuzzy logic and other expert systems in textile processes have the following benefits compared to conventional control techniques (EIPPCB 2003; DyStar 2010; Shim 2009; Shamey and Hussain 2003):

- Improved process control, which can increase productivity and enhance the quality of the final product
- Potential savings in energy and chemicals as a result of the improved process control
- Shorter processing time
- Optimized bath exhaustion
- More reliable processing
- Fewer additions and shading operations
- Reduced effluent load

Block Diagram or Photo

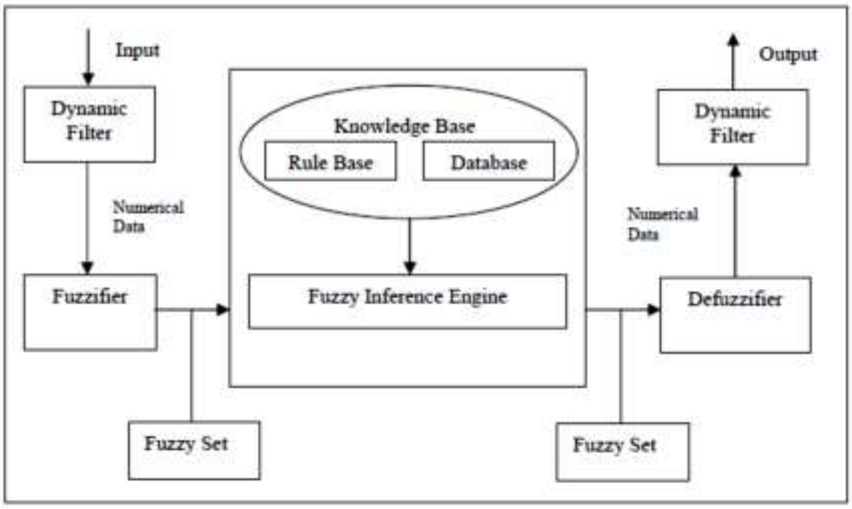


Figure 19. A general fuzzy system with fuzzification and de-fuzzification units and external dynamic filters (Shim 2009)

Commercial Status

Various stages of commercialization depending on the application

References for Further Information

EIPPCB (2003), Shim (2009), Shamey and Hussain (2003), DyStar (2010)

3.5.2. Real-time on-line monitoring systems

Description

Process control by on-line monitoring enhances operation reliability and helps ensure right-first-time production by enabling the operator to evaluate important process parameters in real time. Many systems include predictive models that can quickly adjust operating variables to achieve the desired result (U.S. EPA 1996).

Examples of ongoing research in on-line process control area are (EIPPCB 2003):

- *Dyeing*: chemical oxygen demand (COD) concentration (in relation to dyestuff concentration) is measured on line during washing and rinsing operations in discontinuous dyeing processes. When the dyestuff concentration in the rinse bath is negligible, the rinsing process is automatically stopped. This technique saves considerable water and energy compared to systems that are not monitored in real time.
- *Dyeing and bleaching*: A special amperometric sensor enables on-line control of the concentration of reducing or oxidizing agents in fabrics. For example, the completeness of hydrogen peroxide removal after bleaching or the concentration of reducing agents in vat dyeing can be monitored so that excess chemical use can be avoided.
- *Dyeing with vat dyes*: By monitoring the redox potential, it is possible to detect exactly the point at which the reducing agent is completely rinsed off. When this point is reached, the rinsing process can be stopped and the oxidant added to the bath, which can save water and reduce chemical use and water pollutant emissions

Energy/Environment/Cost/Other Benefits

On-line monitoring systems have the following benefits compared to conventional textile-production control techniques (EIPPCB 2003; U.S. EPA 1996):

- Reduced energy use
- Reduced water consumption
- Reduced use of chemicals/avoidance of excess chemical use
- Reduced re-processing and enhanced right-first-time production
- Reduced load on wastewater treatment facilities

Block Diagram or Photo

N.A.

Commercial Status

Pilot stage

References for Further Information

EIPPCB (2003), U.S. EPA (1996)

Acknowledgments

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