ENERGY CONSERVATION IN WET PROCESSING: DEVELOPMENT OF LOW ENERGY DYEING MACHINE

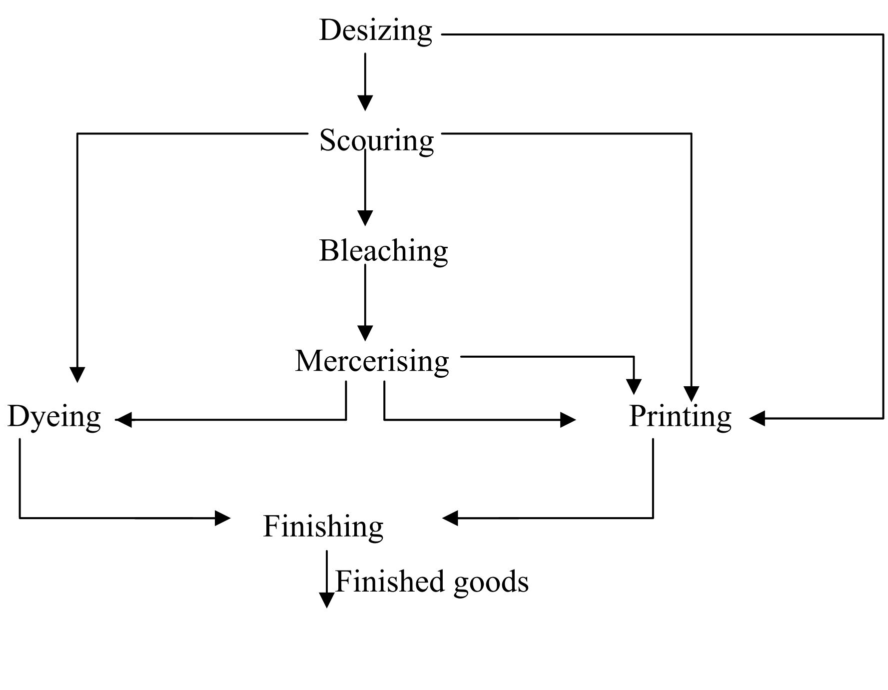
Manisha R. Mathur, M. D. Sankhe and M. K. Bardhan,

The Synthetic and Art Silk Mills' Research Association, Worli, Mumbai - 400 030

Ultrasound technique has been studied and used for a variety of applications in liquids, dispersions and polymers. Ultrasonics holds a promise in applications in the field of textiles. In spite of the varied advantages and simplicity of ultrasonic dyeing, the commercialization of this technique is not reported in literature. SASMIRA has therefore taken up a project sponsored by Department of Science and Technology, Govt. of India, to indigenously develop an Open Width Dyeing Machine of commercial scale incorporating the technique of ultrasound. This article reports in brief the developmental work. The resultant conservation in time and energy during processing has been emphasized.

1. Introduction

Colouration is carried out to impart aesthetic value to the fabric. The colouration process can be either dyeing or printing or a combination of the two processes. There are certain pre-treatments prior to the dyeing/printing processes in order to improve the efficiency of the process. Traditionally these wet processes consume a large amount of water, electricity and thermal energy as the wet processing is exclusively carried out under wet conditions at higher temperatures. Any textile gray fabric has to undergo a series of wet processing sequences before it reaches to the wearer. The probabilities are: -



Most of these process involve the use of chemicals for assisting, accelerating or retarding their rates and must be carried out at elevated temperatures to transfer mass from the processing liquid medium across the surface of the textile material in reasonable time. As with all chemical processes, these transport processes are time and temperature dependent, and compromising either could affect product quality.

1.1. Batch dyeing of Fabric

Conventionally dyeing of textile substrate is an energy intensive process. It requires huge amounts of energy as well as time to accomplish the process. The temperature requirement for cotton and other natural fibre fabric is near boil (90 - 95°C) whereas the synthetic fibre fabrics often require a very high temperature (130°C) and pressure with longer dyeing times. Even with this lengthy time of dyeing, the exhaustion levels obtained are not very satisfactory. Moreover, the conventional dyeing machinery also often poses few limitations during dyeing. Few of the demerits of dyeing textile fabrics with conventional dyeing machinery are as follows:

Open width dyeing of fabric is carried out using Jigger dyeing machine which needs a huge amount of energy to maintain temperatures near boil yet the exhaustion levels of dyeing are often found to be below 70 %. The high temperature – high pressure dyeing of synthetic fibre fabrics is carried out using Jet / Soft flow dyeing machines which are also highly energy intensive machines. Besides, few of these machines require the fabric in rope form leading to dyeing irregularities. Thus, the process does not remain cost effective.

1.2. Novel techniques of dyeing

In order to overcome these difficulties, many non traditional techniques have been put forward to conserve energy in wet processing of textiles [1-4]. These techniques reduce the processing time and energy consumption and maintain or improve the product quality.

Few of the technologies, which have been reported at laboratory scale, are listed below:

- Low temperature dyeing (at boil) is been carried out in presence of carriers. However, many of the carriers in use are found to be non eco-friendly.

- Dyeing in presence of Infrared rays. No commercialisation adopting this technology has been reported so far.
- Low temperature dyeing in presence of Ultra-violet rays. No commercialisation adopting this technology has been reported so far. Moreover, prolonged exposure to UV-rays can also be harmful to human beings.
- Dyeing in presence of super critical carbon dioxide. This technology is expensive and moreover, this technology cannot be incorporated in the existing dyeing machine.

2. Ultrasound Technique

Ultrasonics represents a special branch of general acoustics, the science of mechanical oscillations of solids, liquids and gaseous media. With reference to the properties of human ear, high-frequency inaudible oscillations are defined as ultrasonic or supersonic. In other words, while the normal range of human hearing is between 16 Hz and 16 kHz, ultrasonic frequencies lie between 20 kHz and 500 MHz.

Expressed in physical terms, sound is produced by mechanical oscillation of elastic media. The occurrence of sound presupposes the existence of material; it can present itself in solid, liquid and/or gaseous bodies. Airborne sound is the phenomenon most frequently met during our daily life. It can be directly initiated by excitation of solid bodies, which begin to oscillate and in turn cause the ambient air to vibrate. If the airborne vibrations reach the ear, they are perceived as sound. Air particles being excited to vibrate will in turn excite the adjacent particles, etc., thus causing a periodic series of high pressure and low pressure regions, called condensation and rarefactions, travelling through air in the form of waves [5].

Ultrasonic energy has been attempted on laboratory scale for various wet process in textiles viz., washing, desizing, scouring and dyeing of natural as well as synthetic fibres. It is based on the principle of cavitation. The Basic Principle, Generation of waves, applications in general and textiles in particular and the basic design of the ultrasonic transducer is as given below:

2.1. Basic Principle

In a solid, both longitudinal and transverse waves can be transmitted whereas in gas and liquids only longitudinal waves can be transmitted. In liquids, longitudinal vibrations of molecules generate compression and rarefaction, i.e., areas of high pressure and low local pressure. The latter gives rise to cavities or bubbles, which expand and finally during the compression phase, collapse violently generating shock waves. The phenomena of bubble formation and collapse (known as cavitation) is generally considered responsible for most of ultrasonic's physical and chemical effects observed in solid/liquid or, liquid/liquid systems.

2.2. Generation of Ultrasonic Waves

Ultrasonic waves can be generated in a great variety of ways. Most generally known are the different configurations of whistles, hooters and sirens as well as piezo-electic and magnetostrictive transducers. The working mechanisms of sirens and whistles allow an optimal transfer of the ultrasonic sound to the ambient air. In the case of magnetostrictive and/or peizo-electric transducer of ultrasonic waves, the generators as such will only produce low oscillation amplitudes, which are difficult to transfer to gases. The occurrence of cavities depends upon several factors such as the frequency and intensity of. waves, temperature and vapour pressure of liquids.

2.3. General Uses of Ultrasound

There are many industrial applications of ultrasound, including in the fields of biology/ biochemistry, engineering, geology/geography and medicine where, the application ranges from using high frequency sound to "see" an unborn baby to destruction of stones and cancerous cells inside the body. The application in chemistry is mainly for physical measurements and also as a method of improving reaction rates and/or product yields [6-82].

2.4. Ultrasonics Applications in Textiles

The effects of ultrasound on textile substrates and polymers have started after the introduction of synthetic materials and their blends to the industry. These include application in mechanical processes (weaving, finishing and making-up for cutting and welding woven, nonwoven and knitted fabrics) and wet processes (sizing, scouring, bleaching, dyeing, etc.).

Details of the applications of ultrasound in textile processing are reviewed by the author in previous articles [83-84].

It seems apparent from these publications that ultrasound holds a promise in dyeing of a variety of substrates. In addition, there are a number of patents, which claim beneficial effects produced by ultrasound in dyeing of natural and synthetic fibrous materials. In spite of the varied advantages and simplicity of ultrasonic dyeing, the commercialisation of this technique is not reported in literature. SASMIRA has therefore taken up a project sponsored by Department of Science and technology, Govt. of India, to indigenously develop an Open Width Dyeing Machine of commercial scale incorporating the technique of ultrasound. This article reports in brief the developmental work.

3. Basic Design of the Instrument

The research work relates to modifying the existing commercial scale dyeing machine by way of

- Incorporating ultrasonic transducers into the existing dyeing machine. The dyeing machine has been suitably modified to accommodate the transducers.
- The transducers operate in the frequency range of 20 – 40 kHz.
- The heating mechanism of the existing conventional open width dyeing machine has also been modified. The regular perforated steam heaters have been replaced with three electrical heaters of 5 kW each.
- The control panel is modified to incorporate the ultrasound generators.

The developed jigger mainly consists of the following sub systems:

1. Dyeing section
2. The machine control panel
3. Ultrasonic generator section
4. Tube resonator

3.1. Dyeing Section

The dyeing section is responsible for dyeing operation where fabric dyeing is carried out. The ultrasonic generator provides power to both the tube resonator with required efficiency. Tube resonators are placed in dyeing section at both ends and are the main source of ultrasonic wave emitter in dye bath.

3.2. Machine Control Panel

It consists of different machine controlling switches and indicators.

3.3. The ultrasound generator section

The basic principle and design of an ultrasonic instrument is as follows: The high frequency energy for the process is created in an ultrasonic generator. The frequency of application lies between 20 and 40 kHz. The electronic vibration created by generator is transmitted to the ultrasound head by a shielded wire and converted into mechanical vibrations by ceramic piezo ring. The ceramic rings are fitted into a metal body, which enhances the vibrations. To put the ultrasound into effect, a close contact between the sonotrode and the textile goods is necessary. Thus, the vibrations are transmitted to the material and dye bath.

The developed jigger relates to modifying the existing commercial dyeing machine by way of incorporating these ultrasonic transducers. The generator is a micro processor controlled based with a power of 1000/2000 rms./peak, it generates a frequency of 30+/-3 KHz.

The ultrasonic generator controls the operation of the tube resonators emitting the ultrasonic waves. It houses the individual tube resonator on and off switch and power level indicator (0 – 100 %). The machine is normally operated at a power level of 50 %. Any malfunctioning of the tube resonators is also indicated on this generator, with the help of glowing LED.

3.4 Ultrasonic tube resonators

Tube resonator is the main element, which delivers the ultrasonic waves in to the dye bath. The resonator is in the form of tube with a tube length of 752 mms. The resonator diameter is 48 mm. The resonator is made up of SS – 316 L material.

4. Experimental

The following dyeing were carried out on the commercially developed open width dyeing machine:

4.1. Materials

The fabric particulars are as listed below:

Particulars	**Cotton**	**Silk**	**Nylon**	**Polyester**
Polymer	Cotton	Silk	Nylon	PET
Blend %	100	100	100	100
EPI	48	168	192	80
PPI	56	100	116	76
Warp Yarn	20^s	40^s fil.	Flat fil 46 D	Tex. 164 D
Weft Yarn	20^s	62^s fil.	Flat fil 42 D	Tex. 159 D
G.S.M	140	55	60	111

4.2. Chemicals

Following chemicals of "Laboratory Reagent Grade" and dyes were used for the experimental work.

Sodium chloride
Sodium carbonate
Sodium hydroxide
Sodium sulphate
Sodium dihydrogen phosphate
Sodium sulphide
Hydrogen peroxide
Sodium silicate
Acetic acid
Potassium dichromate

Commercial carrier | Dispersing agent :

Non-ionic detergent | Dispersol F Citamol WS

4.3. Dyes

The following dyes were used for dyeing the above mentioned substrates:

Sr. No	**Name**	Manufacturer	**C.I. No.**
1.	Chikactive Orange ME2R	Chika Overseas	CI Reactive Orange 122 A
2.	Chikactive Navy Blue HE 2R	Chika Overseas	CI Reactive Blue 172
3.	Navinon Jade Green FFB	Indian Dyestuff Industries	CI Vat Green 1
4.	Isolan Red 2SBR	Bayer Industries	CI Acid Red 414
5.	Neolan Blue 2 GX	Ciba Giegy	CI Acid Blue 158
6.	Coomassie Red 2B	I C I	CI Acid Red 249
7.	Rathilne Yellow 3G	Rathi Dye Chem	CI Disperse Yellow 198
8.	Terenix Blue FBL	Jaysynth Dyechem	CI Disperse Blue 56

The fabrics were dyed with different class of dyes using the conventional recipe and also dyed at low temperatures of 50 - 55°C keeping other parameters constant.

The dyed samples were evaluated for their dyeing characteristics. The properties studied during and after dyeing to ascertain their behaviour are as follows:

- Percentage exhaustion
- Percentage fixation of dye on fibre (K/s value)
- Wash fastness of dyed samples
- Wet and Dry rubbing fastness of dyed samples

The test results for these properties are as tabulated in **Tables 1 - 5**:

Table 1 Data for Dyeing Cotton with Reactive Dye

Shade: 1 % M : L :: 1 : 8

Salt : 60 gpl Soda Ash : 20 gpl

Dye	**Chikactive Orange ME2R**		**Chikactive Navy Blue HE2R**	
	Dyeing Technique			
Particulars	Conventional	Ultrasonic	Conventional	Ultrasonic
Temperature, °C	65	50-55	85-90	50-55
Dyeing Time, hrs	2	1.25	3.0	2.1
Exhaustion, %	65	71	68	73
Fixation, K/s	6.54	7.75	4.69	5.93
Wash Fastness	4-5	4-5	4-5	4-5
Dry Rubbing Fastness	4-5	4-5	4-5	4-5
Wet Rubbing Fastness	4	4-5	4	4-5

Table 2 Data for Dyeing Cotton with Vat Dye

Shade: 1 % M : L :: 1 : 8

Hydrosulphite: 10 gpl Sodium hydroxide : 15 gpl

Dye	**Navinon Blue BC**		**Navinon Jade Green FFB**	
	Dyeing Technique			
Particulars	Conventional	Ultrasonic	Conventional	Ultrasonic
Temperature, °C	80	50-55	80	50-55
Dyeing Time, hrs	3.0	2.1	3.0	2.1
Exhaustion, %	68	74	69	75
Fixation, K/s	4.51	5.76	5.61	6.45
Wash Fastness	4-5	4-5	4-5	4-5
Dry Rubbing Fastness	4-5	4-5	4-5	4-5
Wet Rubbing Fastness	4	4-5	4	4

Table 3 Data for Dyeing Silk with Acid Dyes

Shade: 1 % M : L :: 1 : 8
Salt : 40 gpl Acetic Acid : 2 gpl

Dye	**Isolan Red 2 SBR**		**Neolan Blue 2 GX**	
	Dyeing Technique			
Particulars	Conventional	Ultrasonic	Conventional	Ultrasonic
Temperature, °C	80	50-55	80	50-55
Dyeing Time, hrs	2.0	1.25	2.0	1.25
Exhaustion, %	75	79	74	80
Fixation, K/s	2.43	4.53	3.64	5.98
Wash Fastness	4-5	4-5	4-5	4-5
Dry Rubbing Fastness	4-5	4-5	4-5	4-5
Wet Rubbing Fastness	4	4	4	4-5

Table 4 Data for Dyeing Nylon with Acid Dyes

Shade: 1 % M : L :: 1 : 8
Acetic Acid : 2 gpl

Dye	**Coomassie Red 2B**		**Neolan Ble 2 GX**	
	Dyeing Technique			
Particulars	Conventional	Ultrasonic	Conventional	Ultrasonic
Temperature, °C	85	50-55	85	50-55
Dyeing Time, hrs	3.0	2.1	3.0	2.1
Exhaustion, %	70	75	70	74
Fixation, K/s	4.77	6.44	3.53	3.83
Wash Fastness	4-5	4-5	4-5	4-5
Dry Rubbing Fastness	4-5	4-5	4-5	4-5
Wet Rubbing Fastness	4	4	4	4

Table 5 Data for Dyeing Polyester with Disperse Dyes
Dye:

Shade: 1 % M : L :: 1 : 8
Dispersing agent: 2 gpl Acetic acid: 2.5 gpl
Carrier: 2 gpl

Dye	**Rathilene Yellow 3G**		**Ternix Blue FBL**	
	Dyeing Technique			
Particulars	Conventional	Ultrasonic	Conventional	Ultrasonic
Temperature, °C	95	50-55	95	50-55
Dyeing Time, hrs	3.0	2.1	3.0	2.1
Exhaustion, %	73	68	70	68
Fixation, K/s	3.53	2.85	3.19	2.59
Wash Fastness	4-5	4-5	4-5	4-5
Dry Rubbing Fastness	4-5	4-5	4-5	4-5
Wet Rubbing Fastness	4	4	4	4

5. Results and Discussion

The commercial open width dyeing machine was fabricated by suitably altering the existing machine to incorporate the ultrasonic tube resonators. The efficiency of the developed machine was tested by conducting dyeing trials. Different substrates were dyed with different classes of dyes in the same machine in absence (conventional) and in presence of ultrasound (dyeing at 55°C). The dyeing characteristics were studied and compared with the data for similar conventional dyeing characteristics. The findings of the experiments are as follows:

5.1. Percentage exhaustion

The percentage (%) exhaustion of the dye bath was using the Cary 300 UV Visible spectrophotometer. The results are tabulated in **Tables 1 – 5**.

For all substrates dyed with all classes of dyes, it was observed that the % exhaustion was more for the ultrasonic dyeing at 50 °C as compared to the conventional dyeing at high temperature. The increase was found be more pronounced in the case of dyeing of natural fibre fabrics than polyester and nylon dyeing. Thus, for dyeing of cotton with reactive dye, as seen from **Table 1**, the exhaustion level of conventional dyeing was found to be 65 which increased to 71 by dyeing in presence of ultrasound even at a low temperature of 50 °C.

5.2. Percentage fixation, K/s

These values are tabulated in **Tables 1 – 5**. Thus, in case of dyeing of cotton with reactive dye, as seen from **Table 1**, the percentage fixation with conventional technique of dyeing was observed to be 6.03 which increased to 7.75 by dyeing in presence of ultrasound even at a low temperature of 50 °C. The amount of dye being fixed on the fibre surface was found to be more in case of ultrasonic dyeing as compared to conventional dyeing for all substrates and dyes. The increase was found to be more than 50 % in case of dyeing silk fabric (**Table 3**). This is because of the better penetration of dye inside the fibre structure.

5.3. Wash fastness

The results of wash fastness testing for the conventionally dyed as well as ultrasonically dyed samples are depicted in **Tables 1 – 5**. The wash fastness of most of the dyed samples fall in the range of 4 – 5, irrespective of the dyeing method employed. This indicates that the dye being fixed on the fibre surface at 55 °C during ultrasonic dyeing is not superficial but has reacted with the fibre surface.

5.4 Rubbing fastness

The results of dry and wet rubbing fastness of all the dyed samples are tabulated in **Tables 1 – 5**. The testing was carried out on the crockmeter. The ratings for the dry rubbing fastness was found to be in the same range irrespective of the dyeing technique. The wet rubbing fastness, however, was found to be better for few of the ultrasonically dyed samples as compared to the conventionally dyed samples. This could be because of the better fixation of dye on the fibre surface during ultrasonic dyeing. For surface dyeing like polyester, the rubbing fastness was found to be same as conventional dyeing even though the ultrasonic dyeing is carried out at a lower temperature of 50 °C.

6.Discussions

There are many hypothesis explaining the possible action of ultrasound on the dyeing system. Theoretical explanations have been presented which attribute these effect to wave's high energy influencing the dyeing system by means of mechanical or hydrodynamic forces associated with cavitation and by heating of the fibre surface. The influence of ultrasound on the dyeing system are suggested to have threefold effects:

i) Dispersion: breaking up of micelles and high molecular weight aggregates into uniform dispersions in the dye bath.

ii) Degassing: expulsion of dissolved or entrapped gas or air molecules from fibre capillaries and interstices at the crossover of fabric into liquid and removal by cavitation, thus facilitating dye-fibre contact.

iii) Diffusion: accelerating the rate of diffusion of the dye inside the fibre by piercing the insulating layer covering the fiber and accelerating the interaction or chemical reaction, if any, between dye and fibre.

Effect of temperature and molecular weight of the dye

Thus in all cases the temperature yielding the best dye uptake when dyeing with ultrasonic energy was found to be 50 - 55 °C. The higher the relative molecular mass of the dye molecule, the more effective was the ultrasound in increasing the dye uptake. Dye molecules have a tendency to form aggregates when in solution and this tendency increases with increasing r.m.m. Although higher temperatures cause dis-aggregation, the temperatures used during ultrasonic dyeing were not high enough to achieve this effect. Therefore it was the application of ultrasonic energy that broke down the dye aggregates, thus facilitating the increase in dye uptake. With dyes of low r.m.m. the effect was comparatively less pronounced; even in the absence of ultrasound, the dye was able to be adsorbed and to diffuse more readily.

Effect of ultrasound on Substrates

The results of this work show that ultrasound was more effective for dyeing natural fibres like silk and cotton than for dyeing polyester. Dyeing of silk in the presence of ultrasound increased the dye uptake for all the classes of dyes. Dyeing of polyester in the presence of ultrasound did not give results that were as good as those obtainable in conventional dyeing processes at the boil (90-95 °C) with carrier. In comparison, silk, being a fibre with less crystalline structure, is more accessible for dyes and chemicals than are the highly compact polyester fibres. Even after swelling the latter, dye uptake could not be significantly enhanced.

7. Conclusion

The use of ultrasonic energy in physico-chemical processes such as dyeing offers advantages from the point of view of the conservation of energy and time.

The salient features of ultrasonic dyeing can be summarised as follows:

- Low Temperature Dyeing at 50 - 55°C (savings of 40 %)
- Increased Exhaustion & Fixation (increased by 20-25%)
- Reduced Dyeing Time (reduced by 30 %)
- Uniform Dyeing
- Lesser Selvedge to Selvedge Variation
- Lesser Load to Effluent

Thus, the technique of ultrasound dyeing can be effectively implemented in the textile wet processing units for conservation of energy and time with improved dyeing characteristics.

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