INTENSIFICATION OF MASS TRANSFER IN WET TEXTILE PROCESSES BY POWER ULTRASOUND

V.S. Moholkar, V.A. Nierstrasz and M.M.C.G. Warmoeskerken

Textile Technology
Department of Science and Technology
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

E-mail: m.m.c.g.warmoeskerken@utwente.nl

Abstract:

In industrial textile pre-treatment and finishing processes, mass transfer and mass transport are often rate-limiting. As a result, these processes require a relatively long residence time, large amounts of water and chemicals, and are also energy-consuming. In most of these processes, diffusion and convection in the inter-yarn and intra-yarn pores of the fabric are the limiting mass transport mechanisms. Intensification of mass transport, preferentially in the intra yarn pores, is key to the improvement of the efficiency of wet textile processes. Power ultrasound is a promising technique for accelerating mass transport in textile materials. In this paper, the intensification of mass transfer in textiles under the influence of ultrasound on the basis of a total system approach is described. EMPA 101-test fabric was selected as a model for the cleaning process. This study focuses on two aspects, the mechanism of the ultrasound-assisted cleaning process and the effect of the presence of the cloth on the ultrasound wave field generated in a bath. It has been found that the dissolved gas content in the system plays a dominant role in the cleaning process. The cleaning effects observed are explained by two different mechanisms: small-amplitude acoustic bubble oscillations and micro-jets (resulting from the collapse of acoustic bubbles in the boundary layer between the fabric and the bulk fluid) that give rise to convective mass transfer in the intra-yarn pores. It has also been observed that the overall power consumption of the system varies with the position of the fabric in the acoustic field. This variation is explained on the basis of a model involving the specific flow resistance of the fabric and the physical properties of the standing waves.

Keywords:

Process intensification, power ultrasound, acoustic cavitation, enhanced mass transfer

Introduction

Textile process industries are energy- and water-intensive. Wet textile processes such as washing, dyeing, rinsing, de-sizing, scouring and bleaching suffer from two major drawbacks: they require large quantities of water and energy, and need long process times. In most wet textile processes, diffusion and convection in the inter-yarn and intra-yarn pores of the fabric are the dominant mass transfer mechanisms. Intensification of mass transfer is of paramount importance in improving the efficiency of wet textile processes. Conventional methods for intensifying mass transfer in textiles, such as operation at elevated temperatures, are not always feasible, due to unwanted side effects such as fabric damage. Increasing flow through the fabric does not deliver the desired effect due to the complex geometry of the textile materials. Power ultrasound as a means of accelerating mass transfer in textile materials has been attempted in recent years. Several papers have appeared in this field which reported an improvement in energy efficiency and process times of wet textile processes such as dyeing, washing and enzymatic treatments such as bioscouring with the application of ultrasound (for example McCall et al. [1, 2], Thakore [3], Smith and Thakore [4], Rathi et al. [5], Yachmenev et al., [6, 7, 8]). Despite significant research in this area, the exact physical mechanism of the intensification of the mass transfer in the textile materials under influence of ultrasound is not known yet. The main reason for this is the 'black box' approach often used in this area, where the influence of different factors on the overall process such as the frequency and intensity of ultrasound, the condition of the medium, the nature of interaction between the ultrasonic waves and the textile surface are lumped together, and therefore ignored. Moreover, in the application of ultrasound such a black-box approach often results in processes with an unpredictable outcome, unstable processes or inefficient process. This approach impedes the optimisation of ultrasound-enhanced mass transfer, and thus hinders the introduction of this promising technology in the textile industry; for these reasons it should therefore be avoided.

In this work we attempt to study the intensification of mass transfer with the application of power ultrasound on the basis of the total system approach. We have tried to explore the relation between the gas content of the system and the efficiency of the ultrasonic cleaning process. Although the principal focus of this study is to discern the mechanism of the textile cleaning process with ultrasound by using the basic principals of cavitation and ultrasonic wave phenomena, we have tried to throw light on issues that may lead to artefacts during research as well, such as the effect of the presence of a textile on the ultrasound wave field generated in the bath and on the overall power consumption of the ultrasound bath.

Mass transfer in textile materials and ultrasound waves

A piece of textile is a non-homogeneous porous medium. A textile comprises of yarns, and the yarns are made up of fibres. A woven textile fabric often has dual porosity: inter-yarn porosity and intra-yarn porosity. As mentioned earlier, diffusion and convection in the inter-yarn and intra-yarn pores of the fabric form the dominant mechanisms of mass transfer in wet textile processes. The major steps in mass transfer in textile materials are:

- mass transfer from intra-yarn pores to inter-yarn pores,
- mass transfer from the inter-yarn pores to the liquid boundary layer between the textile and the bulk liquid,
- mass transfer from the liquid boundary layer to the bulk liquid.

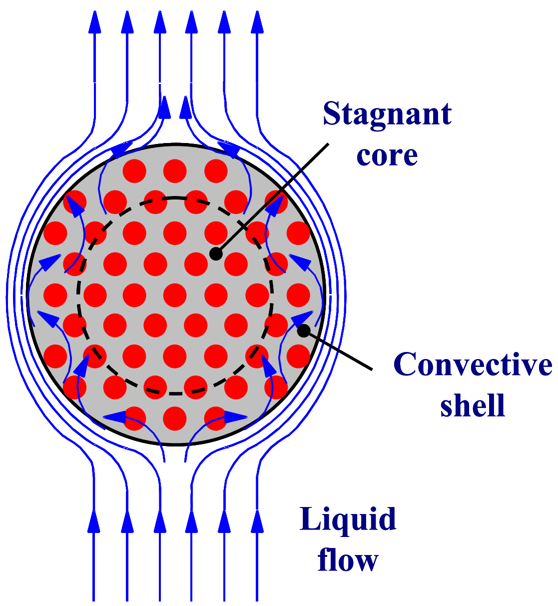


Figure 1. Liquid flow around and through a textile yarn.
The dots represent the fibres in the yarn.

The relative contribution of each of these steps to the overall mass transfer in the textile materials can be determined by the hydrodynamics of the flow through the textile material. Van den Brekel [9], and later Gooijer [10], showed that most of the liquid flow passes the yarns through the inter-yarn pores without penetrating into the intra-yarn pores. This is because the flow resistance in the relatively small intra-yarn pores is much higher than the resistance in the relatively large inter-yarn pores (the inter-yarn permeability is typically larger by a factor of 200 to 2000 than the intra-yarn permeability). The process of mass transfer through the yarns will therefore be driven by diffusion, while the mass transfer between the yarns will mainly be driven by convection. Since the diffusion process is much slower than convection, the rate-determining step in the overall mass transfer will be the diffusion from intra-yarn pores to inter-yarn pores. Warmoeskerken [11, 12] introduced a stagnant-core and a convective-shell model to describe the flows and mass transfer through the yarns. The stagnant core in the yarn is that area in which there is no flow at all; the convective shell is the outer area of the yarn in which the flow penetrates to some extent. The model is given schematically in figure 1. The transfer processes in the stagnant core are based on molecular diffusion, while the transport processes in the outer convective shell are driven by convective diffusion. Since convective diffusion is much faster than molecular diffusion, the rate of soil removal will be determined by the size of the stagnant core. The smaller this core, the faster the removal process will be. This means that the role of mechanical energy, for example, in a wash, dyeing or rinsing process, can be defined as making the stagnant cores in the yarns as small as possible, or the conversion of the slow diffusion process to convection in the yarns, especially in the stagnant core of the yarn.

Squeezing the yarns [12, 13] or the application of power ultrasound [12, 14, 15] in textile pre-treatment and finishing processes can result in convection flows in the yarn, thereby decreasing the size of the stagnant core and enhancing mass transfer. The focus in this paper will be on the intensification of mass transfer using power ultrasound.

Ultrasound is a longitudinal pressure wave in the frequency range above 25 kHz (Figure 2), which is not detected by the human ear. As the sound wave passes through water in the form of compression and rarefaction cycles, the average distance between the water molecules varies. If the pressure amplitude of the sound is sufficiently large, then the distance between the adjacent molecules can exceed the critical molecular distance during the rarefaction cycle. At that moment a new liquid surface is created in the form of voids. This phenomenon is called acoustic cavitation. The theoretical pressure amplitude to cause cavitation in water is approximately 1500 bar. However, in practice acoustic cavitation occurs at a far lower pressure amplitude, less then 5 bar. This is due to presence of weak spots in the liquid in the form of tiny micro-bubbles that lower the tensile strength of the liquid. Cavitation is the principal physical phenomenon behind all the effects of power ultrasound. The word ‘cavitation’ refers to the formation and growth and collapse of vapour or gas bubbles under the influence of ultrasound. For cavitation to occur, the medium must have a large number of nuclei, i.e. cavitation-generating spots. These could be small bubbles already present or arising out of collapsed cavitation bubbles, or these could be gas entrapped in the system at locations such as crevices in the walls of the processor. The volume density of the bubbles is a parameter that cannot be estimated accurately. Nonetheless, an approximate method of qualitatively determining the population of bubbles is to measure the dissolved gas content.

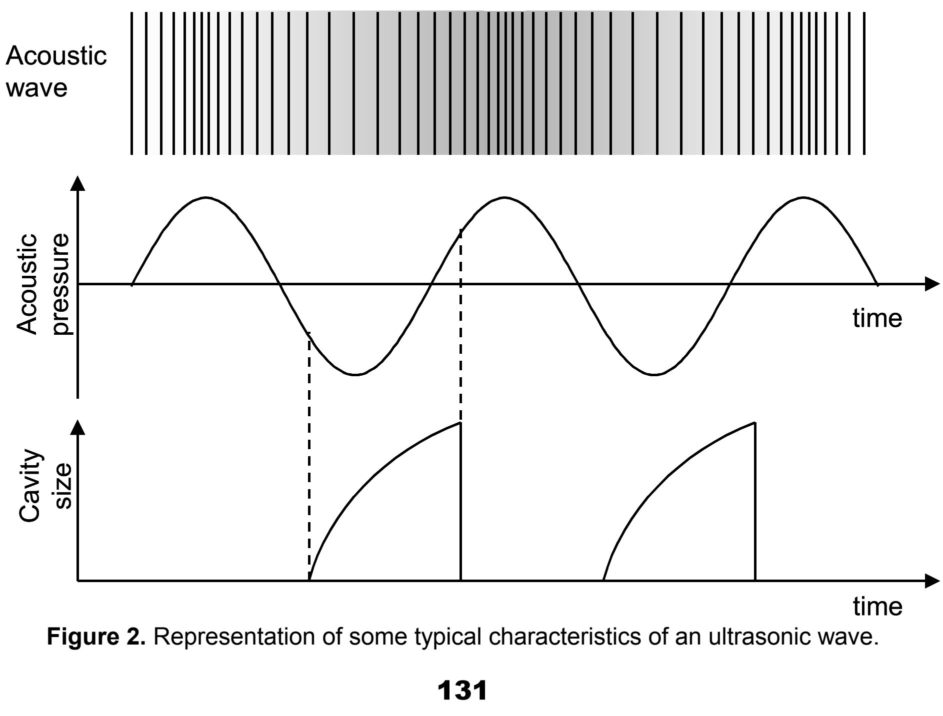


Figure 2. Representation of some typical characteristics of an ultrasonic wave.

Depending on the frequency and intensity of ultrasound waves, these bubbles may undergo a stable oscillatory motion for several acoustic cycles (called *stable cavitation*) or a transient motion comprising of single growth and collapse phase in one or two acoustic cycles (called *transient cavitation*). A detailed study of the dependence of cavitation phenomena on frequency and intensity of ultrasound is given by Flynn [16]. However for acoustic pressure amplitudes exceeding 1 atm and frequencies less than 100 kHz, transient cavitation dominates. If the collapse of the bubbles occurs in the vicinity of a rigid solid surface such as a textile, the bubble undergoes deformation during collapse, which results in the formation of a high-velocity micro-jet with velocities as high as 100-150 m/s directed towards the solid surface (Blake *et al.* [17]). This micro-jet can give rise to intra-yarn flow, thus increasing the rate of the mass transfer between the intra-yarn and inter-yarn pores.
A detailed experimental analysis of cavitation phenomena as a function of the gas content of the medium is given by Blake [18] and Willard [19] who studied the mode of cavitation in water (whether stable or transient) as a function of 2 parameters, namely the gas content of the medium and the pressure amplitude of the ultrasound waves. For low to moderate pressure amplitudes (1 - 1.5 atm), cavitation was observed to be the function of the dissolved gas content. In the case of partially degassed water and high ultrasound pressure amplitudes (> 2 atm), it was seen that the transient cavitation was independent of the dissolved gas content and violent formation, and the collapse of several short lived bubbles was observed. This phenomenon is termed as vaporous cavitation. In vaporous cavitation the bubble population in the medium is independent of the dissolved gas content, since the bubbles are produced *in-situ* by the ultrasound waves.

Experimental

Experimental system

The experiments were carried out in a stainless steel ultrasound bath (Elma Inc., Model D-7700 Singen/Htw.; power 230 W). Figure 3 shows the schematic diagram of the experimental set-up. The dimensions of the bath were as follows: length: 30 cm; width: 30 cm; height: 30 cm. The source of ultrasound in the bath was a detachable sonicator plate. The dimensions of the sonicator plate were as follows: width: 20 cm; height: 20 cm. The sonicator plate had several transducers attached to it on the inside. The frequency of the ultrasound waves generated by the sonicator plate was 30 kHz. The ultrasound bath was equipped with a facility for automatically adjusting the ultrasound frequency according to the variation in the resonance frequency of the transducers. The bath was lined from inside with 3 mm-thick cork rubber. The cork rubber lining acts as an absorber for the ultrasound waves, and therefore prevents random reflections from the walls of the bath, thus giving rise to a unidirectional sound field. The bath had two parallel sliding bars at the top of the sonicator plate to position the fabric frame in the bath. The sliding bars had grooves every 5 mm to assist fixing of the fabric frame at a particular distance from the sonicator plate. A 5 mm-thick stainless steel plate was used as a rigid reflector to create a standing wave field in the bath.

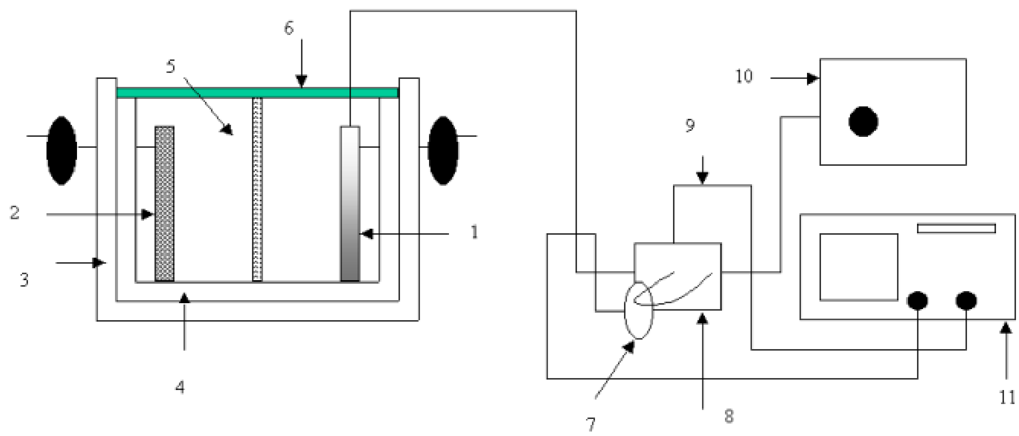


Figure 3. Experimental set-up: 1- Sonicator plate, 2 - Reflector, 3 - Thermal insulation of the bath, 4 - Absorbent rubber lining, 5 - Frame for the textile, 6 - Sliding bar, 7 - Current clamp, 8 - Voltage current monitoring box, 9 - Voltage probe, 10 - Ultrasound amplifier, 11 - Digital oscilloscope.

This plate could be moved with a screw and pinion arrangement to vary the distance from the sonicator plate. A stainless steel frame (length: 20 cm; width: 20 cm) was used to hold the fabric for the ultrasonic treatment. The model fabric used in the experiment was EMPA 101 supplied by EMPA Inc. (ETH, Zurich, Switzerland). EMPA 101 is a cotton test fabric (0.01 g/cm^2) soiled with carbon soot and olive oil. The medium for cleaning of the fabric consisted of 1.75 g/l sodiumdodecylbenzenesulphonate dissolved in demineralised water. For each set of experiments, the bath was filled with 13 litres of washing medium. The dissolved oxygen content of the medium was measured with an oxygen meter (Scott Handylab Inc., Model OX1). The voltage and current supplied to the sonicator plate were monitored on a 2-channel digital oscilloscope (Tektronics Ltd. Model 430A, Bandwidth 400 MHz.) using a voltage probe (Tektronics Ltd., Model 6138A) and a current clamp (Farnell Inc., Model PR 20).

Characterisation of the ultrasound field

The mapping of the ultrasound wave amplitudes was carried out in a plane at a distance of 2.5 cm from the sonicator plate in the standing wave field generated in the bath. This distance is based on the theory of the standing waves and the wavelength of the ultrasound waves (λ) in the bath, which is 5 cm. As such the plane 2.5 cm (distance equivalent to $\lambda/2$) distant from the sonicator is the plane of the pressure antinode. 9 measurement locations were chosen in each plane. Prior to mapping the ultrasound pressure amplitudes, the standing wave field was generated by moving the rigid reflector in front of the sonicator plate. The bath was filled with 13 litres of degassed water with a dissolved oxygen content lowered to 1.98 ppm. The power consumption of the system was monitored with the movement of the rigid reflector. The measurements were carried out with a small hydrophone (Bruel and Kjaer Ltd., Type 8103) connected to a charge amplifier (Nexus Amplifiers, Type 2690) with a sampling frequency of 1 MHz. The bath was placed inside an x-y-z translation system, which was designed to hold the hydrophone at a particular position inside the bath. After mapping the ultrasound pressure amplitudes, measurements of the variation in power consumption of the bath due to the presence of textile were carried out. For this purpose, the model fabric was placed in the frame, and the frame was then moved in the space between the rigid reflector and the sonicator plate. The total power input to the system was monitored with the movement of fabric in the standing wave field.

Techniques for degassing water and textiles

To degas the water, a chemical method was used (van der Vlist et al., [20]). The basis of this method is that CO_2 is bubbled in the water to strip out all the air and to saturate it with CO_2. Later, sodium hydroxide is added to convert all the dissolved CO_2 to carbonate. The pH of the solution was adjusted between 9-10 to ensure the conversion of all CO_2 to carbonate ions. This method can decrease the oxygen content of water to less than 1 ppm of dissolved oxygen. A pressure vessel was used to degas the fabrics. The pieces of the model fabric were cut and placed in sealed plastic bags filled with demineralised water. These bags were placed in the pressure vessel in which the pressure was raised to 7 atm using compressed air. The time for pressurisation was 12 hrs. This was decided on the basis of the theoretical time required for complete collapse of a gas-filled cavity. After pressurisation the plastic bags were opened in degassed water and the fabric pieces were fixed in the frame in order to prevent them from being exposed to air.

Cleaning experiments

The experiments were divided into 4 different sets:

- non-degassed fabric and non-degassed washing medium (NDF-NDW).
- degassed fabric and non-degassed washing medium (DF-NDW).
- non-degassed fabric and degassed washing medium (NDF-DW).
- degassed fabric and degassed washing medium (DF-DW).

In each set, 5 experiments were performed with different pieces of fabric to assess the reproducibility of the results. The fabric frame was placed at a distance of 2.5 cm from the sonicator plate, which is the plane of the pressure antinode with maximum cavitation activity. All fabrics were soaked for 5 min. In each experiment, the voltage and current consumed by the sonicator plate were recorded on the digital oscilloscope with a waveform record length of 30,000. The time of the ultrasonic treatment of the fabric was 3 min. Other details of the experiments can be found in Table 1. To quantify the cleaning effect, the fabric was scanned with a digital scanner (Hewlett Packard Inc., model ScanJet 6300C) to obtain an 8-bit grey scale bitmap image.

Table 1. Details of the condition for the experiments

Set No.	Conditions	Dissolved oxygen content (ppm)	Temperature (^oC)
1	NDW – NDF	9.5	23.4
2	NDW – DF	9.5	23.8
3	DW – NDF	1.98	23.5
4	DW - DF	1.8	23.8

The grey scales of the bitmap image varied from 0 to 255; with 0 and 255 corresponding to the darkest and the whitest pixel respectively. This image was then processed using Corel Photo-Paint software (version 8.0). During the image analysis two main aspects of the image were analysed: the average grey scale of the all pixels and the standard deviation of the grey scales of all pixels. The rationale behind this will be explained in the subsequent section.

Results and discussion

Characterisation and power consumption of the ultrasound bath

The cavitation intensity in an ultrasound bath depends on two factors: the amplitude of the ultrasound waves and the local number density of the bubbles. The local ultrasound pressure amplitude is a measure of the cavitation intensity distribution and hence the energy dissipation patterns in the bath. Figure 4 shows the distribution of pressure amplitude in a plane between the sonicator plate and the reflector. The variation in the pressure amplitudes at different locations can be attributed to the random interference between the ultrasound waves produced by different transducers in the sonicator plate. As such, the pressure amplitude at a particular location is the resultant of the pressure amplitudes of all the waves. The pressure amplitudes at all the locations in the plane are higher than the threshold for transient cavitation, which is approximately 1 atm. It is therefore evident that the mode of cavitation will be transient cavitation at all the locations in this plane.

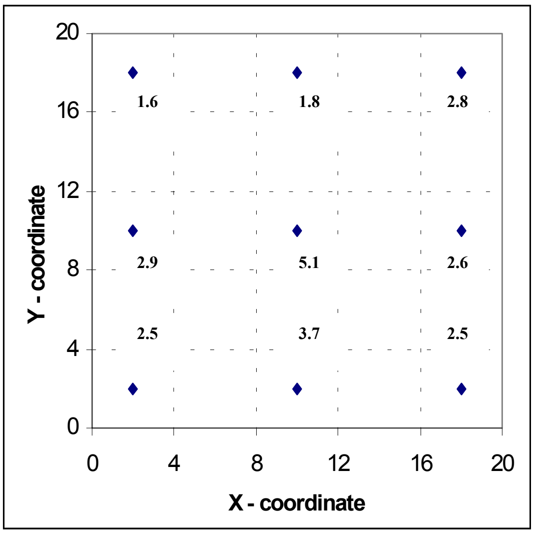


Figure 4. Distribution of the acoustic pressure amplitudes (bar) at different locations in the plane of cleaning experiments between the sonicator plate and the reflector at a distance of 2.5 cm from the sonicator plate.

Figure 5 shows the power consumption of the bath in two cases; firstly as a function of distance between the rigid reflector and the sonicator plate, and secondly as a function of movement of the cloth in the standing wave field between the sonicator and the reflector. It is clear that the power rises sharply when the distance between the sonicator and the reflector is either 2.5 cm or 5 cm. This result can be explained on the basis of the standing wave theory and the theory of the equivalent circuit of the transducers (Pierce [21], Ensminger, [22]). According to this theory, the resistance for the oscillation of the piezoelectric transducer, and hence the power consumed by it, depends on the internal electrical resistance and the acoustic impedance of the medium in which the transducer emits the ultrasound waves. The locations of 2.5 cm and 5 cm correspond to $\lambda/2$ and λ, which are the locations at which resonance occurs in case of a rigid reflector. The acoustic impedance of the medium decreases at resonance, and hence the electric current drawn by the transducer (at a fixed voltage) rises, resulting in an upsurge in power consumption. It can be inferred that the power consumption of the bath reaches the maximum when the textile is positioned at a distance of 1.25 cm and 3.75 cm from the sonicator plate, while the power consumption is significantly lower when the textile is at other positions. Again, the application of the theory of the equivalent circuit of transducers to explain this effect suggests that placing the textile in the standing wave field results in the addition of a space-dependent resistance to the equivalent circuit of the transducers. This resistance can be described on the basis of the transmission loss coefficient of the textile surface, which represents the resistance offered by the textile to the ultrasound waves. It is written as (Pierce [21]):

$$R_{TL} = 10 \log\left(\left| 1 + \frac{1}{2} \frac{R_f}{\rho C} \cos\theta \right|^2 \right) \quad (1)$$

where R_f is the specific flow resistance of the textile and θ is the angle of incidence of the ultrasound waves on the textile surface. It is interesting to note that R_{TL} is independent of the frequency of ultrasound, and hence can be calculated with the flow properties that are estimated with unidirectional flow. If we consider the normal incidence of the ultrasound waves ($\theta = \pi/2$), then R_{TL} is directly proportional to R_f. Gooijer [10] has reported studies in which R_f was measured as a function of the Reynolds number of the flow (Re) through the textile for a unidirectional flow. According to Gooijer's results [10], R_f is inversely proportional to Re for laminar flow. The combination of Gooijer's conclusion [10] and the theory of the standing waves provides a basis for explaining the variation in the bath's power consumption by the position of the textile in the standing wave field. The positions 1.25 and 3.75 cm from the sonicator plate correspond to locations of velocity antinode, where Re of the oscillatory motion of water reaches the maximum. As such, the least resistance is offered by the textile placed at locations of velocity antinode to the ultrasound waves, which results in higher power consumption. This analysis shows that the presence of the textile has a significant effect on the overall characteristics, and hence the performance of the ultrasonic system. Due to a significant variation in power consumption, the results of the cleaning experiments performed with the textile placed at different locations in the bath cannot be compared with each other, and hence cannot be used as a basis for the establishment of the mechanism and the optimisation of the ultrasonic cleaning process.

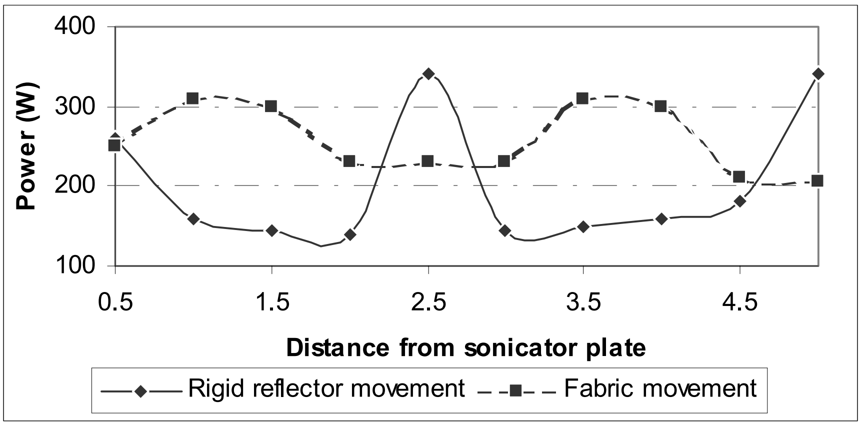


Figure 5. Variation in the power consumption of the bath with reflector movement in front of the sonicator plate, and as a function of textile movement between the sonicator plate and the reflector.

Variation of the cleaning efficiency with process parameters

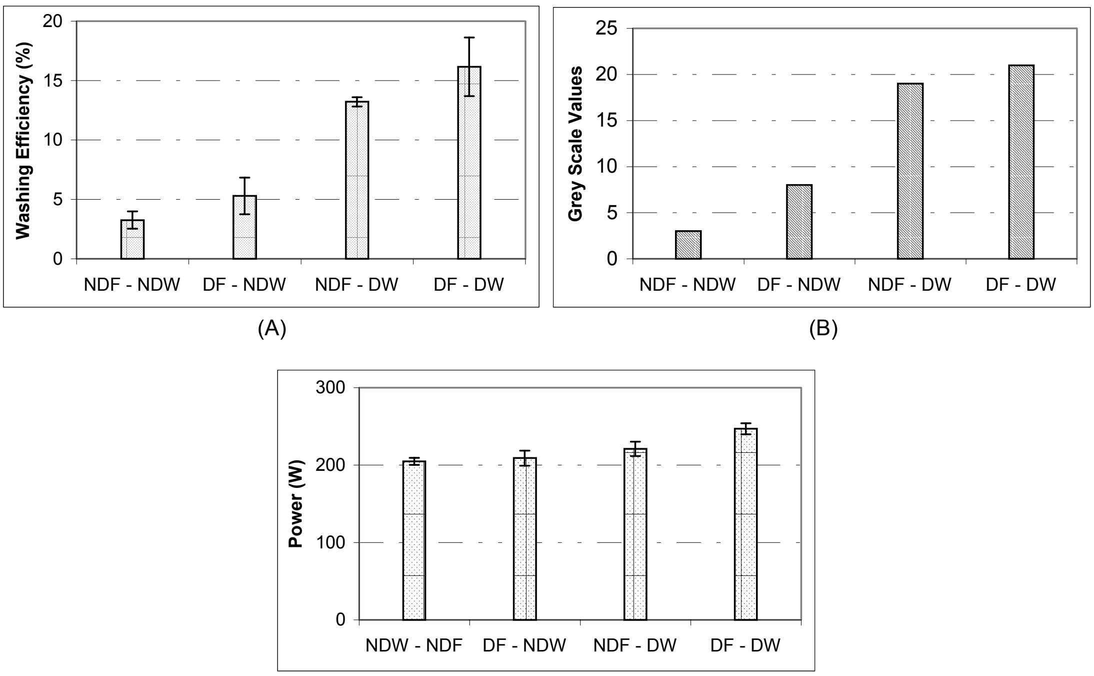
The analysis of variation of the cleaning efficiency mainly focused on two aspects:

- the average grey scale value of the pixels in the fabric sample image, which represents the overall cleaning efficiency of the process, and
- the standard deviation in the grey scale value of the pixels in one single fabric sample image, which represents the uniformity or homogeneity of the cleaning effect on the fabric surface.

The cleaning efficiency (η) is defined on the basis of percentage change in the grey scale as:

$$\eta = \left(\frac{X - Y}{Y}\right) \times 100 \qquad (2)$$

where X is the average grey scale value of a treated sample image and Y is the average grey scale value of an untreated sample image. The trends in η with process parameters are shown in Figure 6A, and the average standard deviations in grey scale of the pixels in different sets of experiments are shown in Figure 6B.



(C)

Figure 6. (A) Cleaning efficiency in different sets of experiments. (B) Average standard deviation in the grey scale values of the pixels in the images of the different samples of different sets. (C) Power consumption of the bath in different sets of experiments.

From Figures 6A and 6B, it can be inferred that the overall cleaning efficiency rises with the decreasing gas content of the system, with an increasing non-uniformity in the cleaning effect indicated by higher values of standard deviation of the grey scale of the pixels with the decreasing gas content of the system. A marked rise in the cleaning efficiency is seen when the washing medium is degassed. Higher standard deviations in the grey scale of the pixels of the samples in the cases of sets 3 and 4 can be attributed to a highly non-uniform distribution of the cavitation nuclei over the textile surface. Figure 6C shows the power consumption of the bath in 4 different sets of experiments. It can be seen that the power consumption of the bath during all sets remains more or less constant. The variation in the cleaning efficiency with the gas content of the system can be explained on the basis of the theory of cavitation. The cleaning efficiency of ultrasound waves is directly proportional to the cavitation intensity, which is a function of the acoustic pressure amplitude and the bubble population. Degassing the washing medium basically reduces the bubble population, which gives rise to *isolated or single bubble cavitation*, and thus assists the cavitation phenomena and its effect in two ways: there is no attenuation of ultrasound waves due to scattering caused by a smaller bubble density per unit volume, and the intensity of the micro-jets developed due to the collapse of bubbles rises due to lower retardation. An interesting observation is that the cleaning efficiency is highest in set 4, where both the fabric and the washing medium are degassed. This effect can be explained on the basis of vaporous cavitation. The comparison of acoustic pressure amplitudes in the plane of washing experiments (Figure 4) to the threshold of vaporous cavitation in partially degassed water (approx. 2 atm) shows that in set 4 vaporous cavitation also contributes to the cleaning effect, due to the very low gas content of the system. As such, the cavitation intensity and hence the cleaning efficiency was highest in set 4.

Conclusions and summary

The present study has explored the dependence of mass transfer intensification in textile cleaning processes on the gas content of the system that comprises a washing medium and a fabric. Different combinations of process conditions reveal that the gas content of the system has a dramatic effect on the cleaning efficiency of ultrasound. The variation in the cleaning efficiencies with different process conditions are explained on the basis of the relation between the cavitation intensity and the dissolved gas content, and on the theory of vaporous cavitation that occurs in partially degassed water at excessively high pressure amplitudes. The second purpose of this paper was to illustrate the secondary effects that contribute to the overall efficiency of any ultrasound-assisted wet textile process. It has been shown that these effects have their origin in the uncontrolled power input to the system. The presence of the textile has a significant effect on the ultrasound field and hence the power consumption of the bath. This paper demonstrates this phenomenon experimentally, and explains it on the basis of the theory of equivalent circuits of piezoelectric transducers in terms of the acoustic impedance [14, 15]. Although the results presented in this paper do not provide sufficient experimental evidence for a firm establishment of the mechanism of ultrasound-enhanced mass transfer in wet textile processing, which has been explored and described in more detail by Moholkar [14, 15], the following conclusions can be drawn:

- The formation of standing waves assists ultrasonic wet textile processing by raising the power consumption of the system, but it also creates regions of non-uniform cavitation activity.
- The presence of a textile fabric in the standing wave field can alter the performance of the ultrasonic system as a whole. Therefore attention should be paid to this secondary effect before interpreting the results of the experiments.
- For an efficient ultrasonic wet textile process, it is of paramount importance to optimise the cavitation intensity. This study provides a simple methodology for optimising the total gas content of the system to meet that goal.

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References

1. *McCall, R.E., Lee, E.R., Mock, G.N., and Grady, P.L., Improving dye yields of vats on cotton fabric using ultrasound. AATCC Book of Papers, (1998) pp. 188-194.*
2. *McCall, R.E., Patel, F.M.A., Mock, G.N., and Grady P.L., Solvent and ultrasonic alternatives to perchloroethylene dry-cleaning of textiles. Textile Colorist and Chemist & American Dyestuff Reporter, Vol 30 No 11 (1998) pp. 11-28.*
3. *Thakore, K.A., Physico-Chemical study on applying ultrasonics in textile dyeing. American Dyestuff Reporter, Vol 79 No 5 (1990) pp. 45-47.*
4. *Smith, C.B. and Thakore, K.A., The effect of ultrasound on fiber reactive dye hydrolysis. Textile Colorist and Chemist & American Dyestuff Reporter, Vol 23 No 10 (1991) pp. 23-25.*
5. *Rathi, N.H., Mock, G.N., McCall, R.E., and Grady, P.L. Ultrasound aided open width washing of mercerized 100% cotton twill fabric. AATCC Book of Papers, (1997) pp. 254-262.*

6. *Yachmenev, V.G., Blanchard, E.J. and Lambert, A.H. Study of the influence of ultrasound on enzymatic treatment of cotton fabric. AATCC Book of Papers, (1998) pp. 472-481.*
7. *Yachmenev, V.G., Blanchard, E.J. and Lambert, A.H. Study of the influence of ultrasound on enzymatic treatment of cotton fabric. Textile Colorist and Chemist & American Dyestuff Reporter, Vol 1 No 1 (1999) pp. 47-51.*
8. *Yachmenev, V.G., Bertoniere, N.R., and Blanchard, J., Effect of sonification on cotton preparation with alkaline pectinase.Textile Res. J., 71 (2001), 527-533.*
9. *Van den Brekel, L.D.M. Hydrodynamics and mass transfer in domestic drum type washing machines. Ph.D. Thesis, Technical University of Delft, Delft (1987).*
10. *Gooijer, H. Flow resistance of textile materials. Ph.D. Thesis, University of Twente, Enschede (1998).*
11. *Warmoeskerken, M.M.C.G., and Boom, R.M., The role of mechanical energy in textile washing. 90^{th} AOCS Annual Meeting & Expo, May 9 – 12, (1999), Orlando, USA.*
12. *Warmoeskerken, M.M.C.G., van der Vlist, P., Moholkar, V.S., and Nierstrasz, V.A., Laundry process intensification by ultrasound. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 210(2-3), 2002, 277-285.*
13. *Van der Donck, J.C.J., So, A., and Frens, G., The influence of stretching on salt release from porous yarns. Tenside Surf. Det., 35 (1998), 119-122.*
14. *Moholkar, V.S., Intensification of textile treatments: sonoprocess engineering. PhD-thesis, University of Twente, The Netherlands, 2002.*
15. *Moholkar, V.S., and Warmoeskerken, M.M.C.G., Mechanistic aspects and optimisation of ultrasonic washing. AATCC Review, 2(2), 2002, 34-37*
16. *Flynn, H.G. Physics of Acoustic Cavitation in Liquids. Physical Acoustics (Vol. ??[[IB]], Ed. W. P. Mason), Academic Press: New York (1964).*
17. *Blake, F.G. Jr., Technical memo 12, Acoustics Research Laboratory, Harvard University, Cambridge, Massachusetts (1949).*
18. *Blake, J.R. Transient cavities near boundaries. Part 1. Rigid boundary. Vol. 170 (1986) pp. 479-497.*
19. *Willard, G.W. 'Ultrasonically induced cavitation in water: a step by step process', J. Acoust. Soc. Am., Vol. 25, (1953) pp. 669.*
20. *Vlist, P. van der, Warmoeskerken, M.M.C.G and Willemse, S. Cleaning process, Eur. Patent No. EP9401241 (1994).*
21. *Pierce, A.D. Acoustics: An introduction to its physical principals and applications. Acoustical Society of America, New York (1989).*
22. *Ensminger, D. Ultrasonics: Fundamentals, Technology, Applications, Marcel Dekker Inc., New York (1988).*