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Mapping of cavitational activity in a pilot plant dyeing equipment

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ABSTRACT

A large number of papers of the literature quote dyeing intensification based on the application of ultrasound (US) in the dyeing liquor. Mass transfer mechanisms are described and quantified, nevertheless these experimental results in general refer to small laboratory apparatuses with a capacity of a few hundred millilitres and extremely high volumetric energy intensity. With the strategy of overcoming the scale-up inaccuracy consequent to the technological application of ultrasounds, a dyeing pilot-plant prototype of suitable liquor capacity (about 40 L) and properly simulating several liquor to textile hydraulic relationships was designed by including US transducers with different geometries.

Optimal dyeing may be obtained by optimising the distance between transducer and textile material, the liquid height being a non-negligible operating parameter. Hence, mapping the cavitation energy in the machinery is expected to provide basic data on the intensity and distribution of the ultrasonic field in the aqueous liquor. A flat ultrasonic transducer (absorbed electrical power of 600 W), equipped with eight devices emitting at 25 kHz, was mounted horizontally at the equipment bottom.

Considering industrial scale dyeing, liquor and textile substrate are reciprocally displaced to achieve a uniform colouration. In this technology a non uniform US field could affect the dyeing evenness to a large extent; hence, mapping the cavitation energy distribution in the machinery is expected to provide fundamental data and define optimal operating conditions. Local values of the cavitation intensity were recorded by using a carefully calibrated Ultrasonic Energy Meter, which is able to measure the power per unit surface generated by the cavitation implosion of bubbles. More than 200 measurements were recorded to define the map at each horizontal plane positioned at a different distance from the US transducer; tap water was heated at the same temperature used for dyeing tests (60 °C). Different liquid flow rates were tested to investigate the effect of the hydrodynamics characterising the equipment.

The mapping of the cavitation intensity in the pilot-plant machinery was performed to achieve with the following goals: (a) to evaluate the influence of turbulence on the cavitation intensity, and (b) to determine the optimal distance from the ultrasound device at which a fabric should be positioned, this parameter being a compromise between the cavitation intensity (higher next to the transducer) and the US field uniformity (achieved at some distance from this device).

By carrying out dyeing tests of wool fabrics in the prototype unit, consistent results were confirmed by comparison with the mapping of cavitation intensity.

1. Introduction

Ultrasounds (US) are cyclic sound pressure waves, with a characteristic frequency higher than 20 kHz, propagating in all media with a sinusoidal dynamics. When these waves propagate in a liquid, they generate compression and rarefaction cycles with possible creation of micro-bubbles, inversely the liquid vapour pressure. The power per unit area required for cavitation depends on the liquid medium and on the content of soluble gases [1]; if tap water is used in sonication, the minimum power intensity necessary to produce transient bubbles is around 0.2–0.3 W/cm^2 [2], an order of magnitude lower than air-free water. Micro-bubbles implode when they change their condition from stable to transient, which define the cavitation mechanism [3]. Typically, applications require a superficial power in excess of the transition state to reach bubbles collapse. At the implosion step, these bubbles create extreme local physical conditions both in terms of pressure and temperature, as high as 100 MPa and 5000 K, respectively [4].

Nowadays ultrasound are considered to implement different innovation fields; indeed, cavitation offers a high potential for intensifying physical, chemical, biological, as well as textile

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Notation

ΔE	total colour difference (–)
D	characteristic length (m)
E	bath exhaustion (%)
E_t	bath exhaustion at time t (mol/L)
E_∞	bath exhaustion at the equilibrium (mol/L)
FH	fabric height (mm)
I	cavitation intensity (W/in.^{2})
I_r	relative cavitation intensity (–)
I_{cavit}	superficial cavitation intensity value by the instrument (W/in.^{2})
$(I_{cavit})_{max}$	maximum superficial cavitation intensity value by the instrument (W/in.^{2})
$I_{cavit,r}$	relative superficial cavitation intensity by the instrument (–)
I_{calor}	superficial cavitation intensity value by calorimetric method (W/in.^{2})
$(I_{calor})_{max}$	maximum superficial cavitation intensity value by calorimetric method (W/in.^{2})
$I_{calor,r}$	relative superficial cavitation intensity by calorimetric method (–)
$I_{r,ave}$	mean value of relative cavitation intensity (–)
K	absorption constant (min^{-1})
LFR	liquid flow rate (L/min)
LR	liquor ratio: weight of the textile material to the dye-bath volume (kg/L)
p	perimeter (m)
PH	probe height (mm)
RSD	relative standard deviation
S	superficial area (m^2)
t	time (min)
$<v>$	average superficial liquid velocity (m/s)
WD	water depth (mm)
Greek letters	
ρ	liquid density (kg/m^3)
μ	liquid viscosity (Pa s)
λ	wave length (m)

processes [5–7]. As far as textile technologies are concerned, US have been used since the 1950s to improve dyeing of natural fibres thanks to a reduction of the operating temperature and process time [8]. It appeared that micro-bubble cavitation is strongly affected by several parameters, namely temperature and hydrodynamics of the system. Recently it was demonstrated that the effectiveness depends on the distance between the fabric and the ultrasonic transducer [9]. As a consequence, the characteristic distribution of the energy produced by cavitation phenomena must be evaluated to govern the intensification of the processes considered.

Starting from the late '80s, researchers have begun to study the enhance of dyeing by US application, considering kinetics and transport phenomena with specific emphasis. From these studies, the advantages induced by ultrasounds have appeared:

- reduction of thickness and stability of the boundary layer between fibre and dye-bath;
- increasing of dyestuff diffusivity in and between fibres;
- decreasing dyestuff aggregation in a dye-bath and consequently increasing dye dissolution [10–12].

A large number of studies on acoustic cavitation have been carried out since the end of the '90s to enlighten the mechanisms related to transport phenomena and kinetic improvement [9–11,13].

Most of the cited studies refer to application on bench scale apparatuses, characterised by nominal volumetric density as high as 4 kW/L (this value hinders any scale-up trial), whilst very few data on pilot scale exists. For this reason, in order to overcome the uncertainty of scaling-up the technological application of ultrasounds, in the frame of the Piemonte Regional Project INTEXUSA (INnovation in TEXtile productions by UltraSound Application), a dyeing prototype of suitable size was conceived, designed and built. Thanks to the operating flexibility of this equipment several textile substrates (fabric width up to 0.4 m, 4 hanks with an overall weight of about 3 kg and garments with an overall weight of 0.5 kg) can be processed either following standard dyeing procedures or intensifying dyeing thanks to ultrasonic-promoted cavitation. The hydrodynamics of the liquid flow was simultaneously controlled. The dyeing performance was regulated by optimising the reciprocal position between the transducer and the textile material. Hence, mapping the cavitation energy in the machinery is expected to provide fundamental data on the intensity and distribution of the US field in the aqueous dyeing liquor.

The aims of the present work are:

(a) mapping the cavitation intensity by a diagnostic probe in the pilot plant equipment to define the maximum liquid flow rate to be used and the best position of the textile material respect to the transducer;
(b) validating these conditions with dyeing tests.

2. Materials and methods

2.1. Ultrasonic prototype equipment

The pilot equipment is constituted of a stainless steel parallelepiped tank, connected with a centrifugal pump for the circulating the process liquid and equipped with an external heating system to maintain the desired temperature. The liquid is distributed homogeneously along one side of the vessel, thanks to a perforated pipe, and is then discharged on the opposite site. A removable frame is placed in the vessel to hold a reel and a series of driven and dummy cylinders to obtain a regular circulation of a given length of fabric. Alternatively, several yarn hanks can be held by the heel, while a perforated cylinder suitably immersed in the liquor could process garments for dyeing and washing operations. The mentioned configurations can be easily commuted, depending on the type of textile material. The parallelepiped vessel has a base of 560 × 440 mm, the maximum liquid height tested being 165 mm for a total maximum liquid volume of about 40 L. A comprehensive representation is given in Fig. 1.

In the bottom of the vessel a plane transducer, a flat SONOPLATE® (400 × 300 mm) US emitting device made by Weber Ultrasonics GmbH, is installed. It is constituted of 8 cone-shaped transducers, mounted on a stainless steel plate. The generator, connected with the transducers, was characterised by a maximum power input of 600 W at a fixed 25 kHz frequency; the nominal volumetric energy density is 15 W/L. A top view of the apparatus is shown in Fig. 2.