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Ultrasonic washing of textiles

Junhee Choi [a], Tae-Hong Kim [a], Ho-Young Kim [a,*], Wonjung Kim [b,*]

[a] Department of Mechanical and Aerospace Engineering, Seoul National University, Seoul 151-744, Republic of Korea
[b] Department of Mechanical Engineering, Sogang University, Seoul 121-742, Republic of Korea

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ABSTRACT

We present the results of experimental investigation of ultrasonic washing of textiles. The results demonstrate that cavitation bubbles oscillating in acoustic fields are capable of removing soils from textiles. Since the washing performance is mitigated in a large washing bath when using an ultrasonic transducer, we propose a novel washing scheme by combining the ultrasonic vibration with a conventional washing method utilizing kinetic energy of textiles. It is shown that the hybrid washing scheme achieves a markedly enhanced performance up to 15% in comparison with the conventional washing machine. This work can contribute to developing a novel laundry machine with reduced washing time and waste water.

1. Introduction

Before the advent of washing machines in the late 19th century [1], the laundry was done by the use of hands or tools such as clubs and bats. The laundry is still done in this manner in some less industrialized regions. In the manual laundry, mechanical forces are exerted on the dirt adhering to textiles by scouring, twisting, or beating. Washing machines use electric power to replace human labor for producing the mechanical forces. In particular, the rotation of washing bath induces a liquid flow to generate mechanical actions such as deformation and scouring of textiles, thereby removing the dirt [2,3]. In addition to the chemical effect of detergent loosening the dirt from textile surfaces, mechanical actions by washing bath are principally responsible for the textile washing.

Recently, attempts have been made to use acoustic cavitation for washing textiles. Ultrasonic cleaning has been widely employed to remove submicron-sized contaminant particles adhering to solid substrates (e.g., photomasks and wafers) in semiconductor industry [4,5]. Ultrasonic waves traveling in a liquid result in cavitation and thus produce bubbles [6]. The bubbles exhibit rich dynamic behaviors such as translation, oscillation, growth, and collapse in response to the varying acoustic pressure [6]. Moholkar et al. examined the effect of acoustic cavitation on washing textiles which were placed at pressure nodes and antinodes in a standing-wave field [7]. Their experiment showed that the textiles were exclusively cleaned at the antinodes where acoustic cavitation is mainly generated, suggesting that acoustic cavitation is a main factor for textile washing. Juarez et al. showed that the ultrasonic system with the acoustic intensity higher than approximately 0.4 W/cm^2 had better washing results in comparison to conventional washing machines [8].

However, ultrasonic washing has some critical weaknesses in terms of cleaning range [8]. The dynamic motions of cavitation bubbles occur through the interaction with acoustic waves, which are unduly inactive at the far fields due to the attenuation and reflection. Thus, the effects of ultrasonic washing are limited to the near field of the transducer, which has presumably impeded the development of ultrasonic washing machines for practical uses.

We here investigate the cleaning effects of acoustic cavitation for textiles. We theoretically analyze the detachment forces induced by acoustic cavitation, which are proved to be comparable with the adhesion forces of particles on the textile. The analysis is supported by the high-speed visualization of the particle removal from the textile by cavitation bubbles. We then develop an ultrasonic washing system combined with a commercial washing machine. Our experimental results demonstrate that the hybrid scheme can achieve enhanced cleaning performance.

2. Removal forces on a particle by an oscillating bubble

We estimate the adhesive force of carbon black particles on a standard specimen textile (EMPA 106, Testfabrics) made of cotton fabric. Fig. 1 presents SEM (Scanning Electron Microscopy) images indicating that nano-sized carbon black particles form aggregations sized on the order of 1 μm. We may thus assume an aggregation of carbon black as a single particle with a radius of approximately 1 μm. The strength of adhesion of a micron-sized

* Corresponding authors.
E-mail addresses: hyk@snu.ac.kr (H.-Y. Kim), wonjungkim@sogang.ac.kr (W. Kim).

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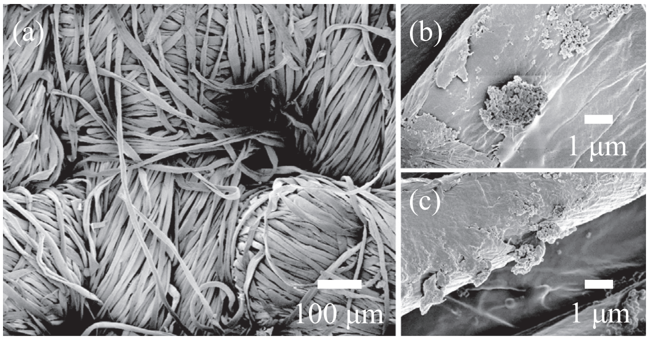

Fig. 1. SEM images of carbon black particles adhering to the textile. (a) Texture of the contaminated specimen textile. (b and c) Carbon black aggregations on the textile.

particle to a flat substrate is generally given by the van der Waals force expressed as $F_v = AR/(6Z_0^2)$, where A is the Hamaker constant, R the aggregation radius, and Z_0 the distance between the aggregation and the surface [9,10]. When the particles deform and adhere to a substrate, the total adhesion force F_{ag} increases to $F_{ag} = F_v(1 + a^2/RZ_0)$, where a is the contact radius [9]. Neither the deformed shapes of carbon black particles nor the surface geometry is easily determined on the basis of the SEM observations. However, when a particle adheres to a solid surface, the contact radius is usually given by the Johnson–Kendall–Roberts (JKR) theory, $a \sim [6\pi WR^2(1/E_1 + 1/E_2)]^{1/3}$, where W is the surface free energy of solid surface, and E_1 and E_2 are the elastic moduli of the particle and solid substrate, respectively [11]. The surface free energy of cotton fabric is of the order of 2×10^{-2} J/m^2 [11], and the elastic moduli of cotton fabric and carbon black are 30 [12] and 27 GPa [13], respectively. Therefore, we obtain the contact radius of approximately 30 nm. In addition, we assume that $Z_0 \sim 1.6$ nm and $A \sim 3.3 \times 10^{-20}$ J, which correspond to a carbon black particle on cellophane immersed in water [14]. Consequently, our analysis yields a rough estimation of the adhesion torque $\tau_{ag} \sim aF_{ag}$ of the order of 10^{-16} N m.

The dynamic motion of an acoustic bubble is responsible for the particle removal [9]. Recently, our group characterized the motions of cavitation bubbles in ultrasonic field and classified into four modes: volume oscillation, shape oscillation, splitting, and chaotic oscillation [15]. Depending on the radius of a bubble and acoustic pressure, a specific oscillation mode is predominant. The pressure field around an oscillating bubble is the most powerful in the chaotic oscillation mode, and followed by those in splitting, shape oscillation, and volume oscillation modes.

The chaotic oscillation of an ultrasonic bubble occurs at a relatively high acoustic pressure if the radius of the bubble is comparable to that of a resonant bubble, which is given by Minnaert's formula $R_b = (3kP_0/\rho)^{1/2}/\omega$, where k is the adiabatic exponent, P_0 the ambient pressure, ρ the liquid density, and ω the angular frequency [16]. Because the dominant contents of bubbles are oxygen and nitrogen, the adiabatic exponent k is approximately 1.4 [9]. In our ultrasonic system with an acoustic frequency of 20 kHz, R_b is approximately 100 μm. It has been experimentally observed that a chaotically oscillating bubble induces the localized liquid flow with a speed v of ∼10 m/s, which generates a dynamic pressure $\rho v^2 \sim 10^2$ kPa [15], thereby resulting in the removal torque $\rho v^2 a^3 \sim 10^{-13}$ N m. A chaotically oscillating bubble entails a liquid jet with a speed of ∼10^2 m/s, which induces a water hammer pressure $\rho cv \sim 10^2$ MPa, and shock waves with a pressure on the order of 10^2 GPa [17]. Therefore, the removal torque by chaotic oscillation greatly exceeds the adhesion torque.

We examine that the aggregated carbon black particles can be removed by the volume oscillation of the bubble, the weakest mode. The volume oscillation is observed when the acoustic pressure is relatively low or when the bubble radius is significantly different from the resonance radius. An radially oscillating bubble with an angular frequency ω and radius R_b produces the radial velocity field given by $v \sim \omega R_b(R_b/r)^2$, where r is the radial distance from the center of bubble. The dynamic pressure $P \sim \rho v^2$ decreases with the distance from the bubble. Therefore, the pressure gradient is scaled as $|\partial P/\partial r| \sim \rho\omega^2 R_b(R_b/r)^5$ near a resonant bubble, and this pressure gradient exerts a thrust of the order of $R^3|\partial P/\partial r|$ on a particle sitting near the bubble. Accordingly, the detachment torque due to the dynamic pressure can be expressed as $\tau_d \sim (8\pi/3)\rho\omega^2 R^4 {R_b}^6/r^5$, so that the detachment torque τ_d is on the order of 10^{-16} N m near the bubble interface where $r \sim R_b$, which is comparable to the detachment torque.

3. Visualization of particle removal

We visualize the effects of acoustic cavitation on particle removal. We constructed the experimental apparatus consisting of a transparent bath filled with water, a flow-horn type transducer (UP400S, Hielscher), an upright microscope (Olympus BX-51M) with a water immersion objective lens (Olympus LUMPLEL 10XW), and a high-speed camera (Photron SA1.1), as shown in Fig. 2. We visualized the cleaning process at a rate of 10,000 frames per second. The transducer with a diameter of 2.2 cm produces ultrasonic waves with a frequency of 20 kHz and an intensity of 40 W/cm^2. To visualize the process of contaminant removal, we used the microparticles (IDC Latex particle, Life technology) with 4 μm in diameter because the nano or submicron sized carbon black particles cannot be clearly shown with the optical lens. The microparticles were attached on a textile by placing a drop of the ethanol solution of microparticles. We waited 30 min to regulate the adhesion force before immersing the textile in the bath.

Fig. 3 shows the sequential images of the microparticle removal by an acoustic bubble. The microparticles adhering to the textile are trapped between the fibers, and detached by a chaotic bubble. This is the first visualization result, to the authors' knowledge of the particle removal from textiles due to an acoustic bubble.

4. Washing performance depending on distinct washing schemes

We proceed by analysis of the dependence of the performance of the ultrasonic washing on the acoustic intensity and the volume of washing medium. We placed the same transducer shown in Fig. 2 in a small beaker filled with the detergent (AHAM HLW-1 Formula III) solution with a mass concentration of 3000 ppm. The

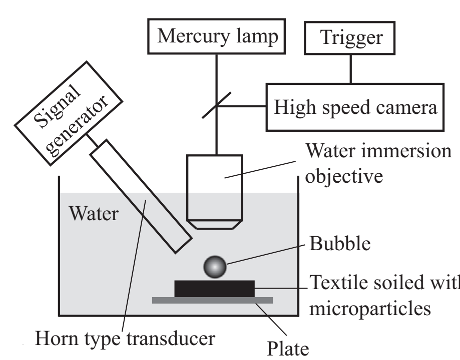

Fig. 2. Schematic illustration of the visualization apparatus.