The Role of Surface Tension on the Residual Water Content of Fabrics

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ABSTRACT: Cotton has been shown to hold up to 80% of its initial weight in water due to strong capillary forces after washing. According to the LaPlace equation for capillary rise, the rise is proportional to the surface tension of the air–liquid interface. The use of a tailored rinse additive has the potential to alter the surface tension of solutions significantly, thus leading to a lower capillary rise. This lower rise can be related to the residual water content in fabrics. The reduction of surface tension lowers the force required to displace liquid inside the capillaries formed by fabric fibers. If the amount of residual water in fabrics can be significantly lowered, the drying time of the fabrics would be decreased as well. We have shown that by reducing the surface tension of solutions, the residual moisture content of fabrics also decreases.

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The use of household laundry machines and dryers has become a necessity in the everyday lives of most people. Today's society has become rushed and people have less and less time to spend on everyday household chores such as laundry. Because of this lack of free time, consumer polls have shown that consumers want a significant reduction in the drying time of their laundry in order to have more free time. In addition, the energy spent (and hence the time required) in drying fabrics depends on the residual moisture content (RMC) of the fabric after the spin cycle in the washing machine. If we reduce the RMC by 30%, we will spend 30% less energy and 30% less time in drying the fabric. In the United States, such a 30% reduction of the RMC has the potential to save over $900 million dollars per year in energy costs in addition to saving time for the consumer.

The role of surface tension as a key aspect of the laundry process has been identified as reducing the drying time of fabrics. The rationale is that if the amount of residual water in fabrics can be reduced during the spin cycle of the washing machine, that would correspond to a reduction in drying time during the drying cycle. It is assumed that capillaries in the fabric structure created by overlapping fabric fibers hold the water.

The LaPlace equation for capillary rise (Eq. 1, where h is the capillary height, γ is the surface tension, θ is the contact angle, r is the capillary radius, ρ is the solution density, and g is the gravitational constant) predicts that the capillary height (which can be related to RMC) is proportional to the surface tension. Therefore, as the surface tension decreases the RMC of the fabric should decrease as well.

$$h = \frac{2\gamma\cos\theta}{r\rho g} \qquad [1]$$

The amount of fluid that can wick into a capillary is proportional to the surface tension of the fluid. Equation 2 shows that the work required to move a liquid a given distance is proportional to the surface tension:

$$W = \gamma \cdot \Delta A \qquad [2]$$

Based on Equation 2, if the surface tension (γ) of the fluid is lowered and the work (W) is held constant (the centrifugal force exerted on the fabric during the spin cycle), then the amount of displacement in the capillary (ΔA) must increase to balance the equation. Therefore, based on these principles, if the surface tension of the rinse water can be lowered before the final spin cycle, then more water will be forced out of the fabric. If less water is present in the fabric before placing in it the dryer, then the time required to dry the fabric will be decreased.

Preston *et al.* (1) have shown that water is retained in moist fibers as capillary water held in the spaces between fibers and as hydrates of the fiber molecules. They have also shown that the amount of moisture retained in viscose and cellulose fibers is proportional to the surface tension of the solution. However, their studies have mainly focused on the surface tensions of two different solutions and on a fixed centrifugal time.

If, by using appropriate additives, the surface tension of a formulation can be substantially decreased, then the centrifugal forces in the spin cycle of existing machines can remove more water. This approach was used successfully in earlier work on enhanced oil recovery, where similar capillary forces responsible for trapping oil in the fine pores of

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Abbreviations: DOE, U.S. Department of Energy; RMC, residual moisture content.

an oil reservoir were eliminated or reduced by reducing the interfacial tensions (2).

Shah (3) found a striking change in the properties of various systems (e.g., lecithin–cholesterol, stearic acid–stearyl alcohol, decanoic acid–decanol, potassium oleate–hexanol, sodium dodecyl sulfate–cetyl pyridinium chloride) at a 1:3 molecular ratio. Although direct surface tension values were not reported for these systems, in all cases there was indirect evidence (e.g., evaporation rate, foam stability, solubilization in a microemulsion) that at this ratio there was a crowding of molecules at the interface and that the molecules were tightly packed. Other researchers have reported this synergism for anionic/cationic (4), anionic/zwitterionic (5–7), cationic/zwitterionic (5), nonionic/zwitterionic (5), anionic/cationic-gemini (8), anionic-gemini/zwitterionic (9), cationic-gemini/nonionic (10), and cationic-gemini/sugar surfactants (11). These investigations suggest that properly engineered synergism can help reduce surface tension values to *ca.* 20 mN/m.

EXPERIMENTAL PROCEDURES

To test the effect of surface tension on the residual water content of fabrics, we made several assumptions. After several force calculations, we determined that the average household washing machine spins with a force of about 90 times the force of gravity. For testing purposes, each fabric sample was soaked for 10 min and then placed in the centrifuge for 10 min. The experimental apparatus is shown in Figure 1. The setup uses a centrifuge tube with a copper insert. The copper insert has a closed end, with the other end flared so that it will not fall inside the outer tube. The insert also has small holes drilled through it to allow water to drain through the insert into the collection tube (much in the same way a modern washing machine is designed).

Several different types of fabric were used in the experiments. For the initial experiments, three samples were used. Two fabrics were 100% cotton (a denim fabric and a plain cotton fabric), and the third fabric was a 65/35% polyester–cotton blend. For RMC testing, the first type of fabric tested was a U.S. Department of Energy (DOE) standard test fabric, a 50/50% blend of polyester and cotton. A 100% cotton Hanes (Winston-Salem, NC) T-shirt material and an 86/14% cotton–polyester terry cloth were also tested.

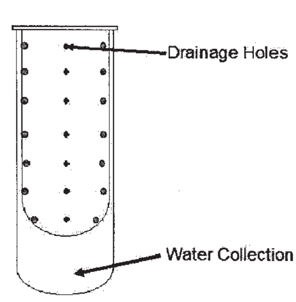

FIG. 1. Experimental setup used to determine the residual moisture content (RMC) of fabrics.

After the fabric was soaked and centrifuged, the weight was then taken to determine the RMC, as shown in Equation 3. The first sets of experiments were designed to obtain basic information about how the system acts (such as force and time dependence on the RMC).

$$\mathrm{RMC} = 100 \cdot \frac{\mathrm{weight}_{\mathrm{centrifuged}} - \mathrm{weight}_{\mathrm{dry}}}{\mathrm{weight}_{\mathrm{dry}}} \qquad [3]$$

Surface tension measurements were made using the Wilhelmy plate method. In this method, the output from a gram-force sensor holding the plate is sent to a transducer and then to a voltage readout. The system was calibrated using two known solutions (water at 72.5 mN/m and acetone at 23 mN/m). The platinum plate was heated using a torch between each reading to clean off anything that may have adsorbed onto the plate. For the experiments performed, only the equilibrium surface tension was correlated with the RMC of the fabrics.

With a basic understanding of how the system acted under different forces, we desired to determine the relationship between RMC and surface tension. Several sets of experiments were performed using various commercial surfactants provided by the manufacturer (DeIonic 100-VLF and DeIonic LF60-MOD from DeForest Enterprises, Boca Raton, FL; Dow Corning Q2-5211 from Dow Corning Corp., Midland, MI). All of the commercial surfactants were tested at 1000 ppm (0.1 wt%). Several other surfactant systems were chosen in this study as well. A leading detergent (at 1500 ppm, the normal household dosage in a washing machine) and a leading fabric softener (at 500 ppm, the household dosage) were also tested in these experiments.

The first set of experiments was performed using the same surfactant but varying the surface tension by using different surfactant concentrations. Since a trend was observed, another set of experiments was performed to determine whether this relationship would hold true for different surfactants with varying surface tensions.

RESULTS

As shown in Figure 2, the RMC decreased exponentially with increasing gravitational force. This was expected since a higher force was being placed on the system as the centrifugal speed was increased. The denim and cotton samples (both 100% cotton) showed approximately the same RMC as a function of gravitational force, whereas the 65/35% polyester–cotton sample was much lower. This was due to the change in contact angle of the water on the fabric. Since polyester is hydrophobic, the contact angle was increased and the capillary height was decreased, resulting in a lower RMC. Additionally, as the residence time in the centrifuge increased, the RMC decreased (Fig. 3). This was due to the fluid overcoming the viscous forces in the capillaries. Since the force was not being increased, the only factors holding the water in the fabric were surface tension and viscous forces. As the residence time was increased, the system had time to equili-

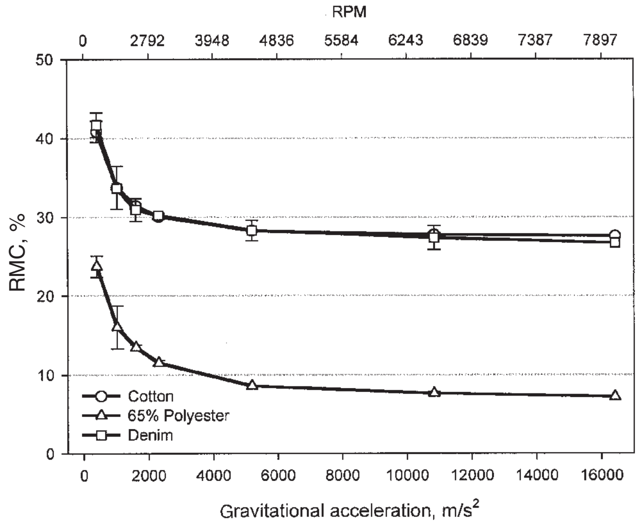

FIG. 2. The effect of variations in gravitational force on the RMC of various fabrics. For abbreviation see Figure 1.

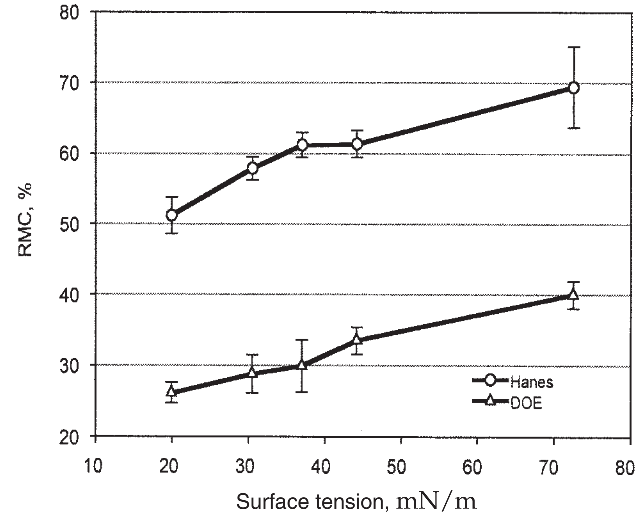

FIG. 4. Relationship between the RMC and surface tension for the detergent system at 1000 rpm (*ca.* 92 times the force of gravity) for 10 min. Hanes, 100% cotton T-shirt material (Hanes, Winston-Salem, NC); DOE, U.S. Department of Energy standard test fabric, a 50/50% polyester–cotton blend; for other abbreviation see Figure 1.

brate, and all unbound water was able to be displaced from the fabric.

After we had established a basic understanding of how the system reacted to different forces, we focused attention on determining the relationship between the RMC and surface tension. To determine whether there was a relationship between the surface tension of a solution and the RMC of the fabrics, the RMC were measured for different solution concentrations of the leading detergent. Figure 4 shows a smooth trend in the relationship between the RMC of fabrics and the surface tension. Since the lowest surface tension achieved using the detergent solutions was *ca.* 30 mN/m, Dow Corning Q2-5211 was used as a reference point (at 19.9 mN/m) (see Fig. 4). If one extrapolates these curves to a surface tension of zero, one might assume that the trapped water was simply the water of hydration caused by strong hydrogen bonding between the fabric and water. However, many microcapillaries are present in the fabric structure. Under force, these capillaries may close due to the crushing of the fabric under load, trapping water inside the fabric structure.

Since a clear relationship existed between the surface tension of a solution and the RMC of the fabrics, more experiments were performed using a variety of surfactant types to determine whether a general correlation existed independent of

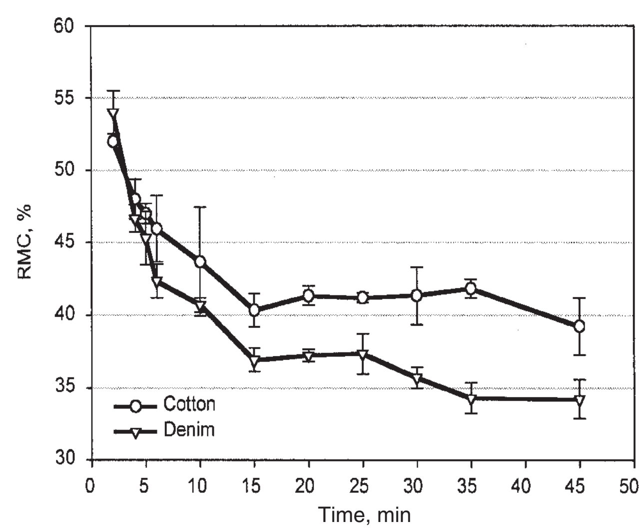

FIG. 3. The effect of variations in time of centrifugation on the RMC of various fabrics. For abbreviation see Figure 1.

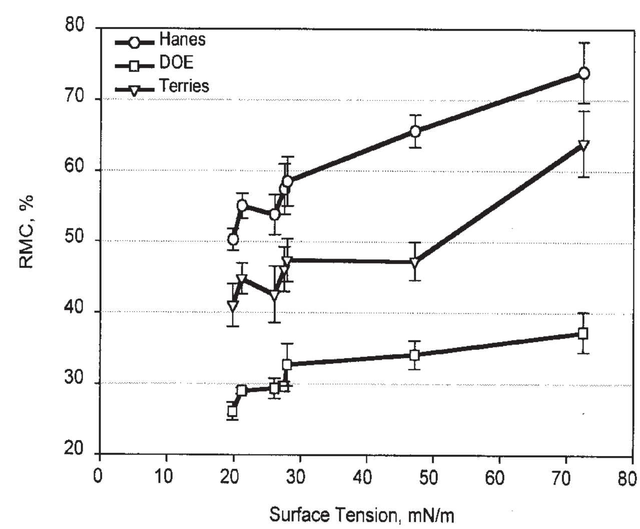

FIG. 5. Relationship between the RMC and surface tension for commercial surfactant systems at 1000 rpm (*ca.* 92 times the force of gravity) for 10 min. Terries, 86/14% cotton–polyester terry cloth; for other fabrics see Figure 4; for abbreviation see Figure 1.

surfactant type. As shown in Figure 5, a relationship between the RMC of the fabrics and the solution surface tension existed for various commercial surfactant systems; however, a few discrepancies were present. The range of surfactant types used may account for such disturbances in the trend. Several different types of surfactants (ionic, nonionic, and siloxanes) were used in this experiment, and each type may have had some sort of interaction with the fabric surface, causing more or less water to be displaced during centrifugation.

A strong relationship did exist between the RMC of the fabrics and the surface tensions of the solutions, as also shown by Preston *et al.* (1). This can be attributed to the surface tension found in the LaPlace equation (Eq. 1). However, one should note that a much clearer relationship existed in a homogeneous series (Fig. 4) than when different surfactant systems were used to vary the surface tension (Fig. 5). The main problem encountered in the reduction of water content was achieving a system with low surface tension (lower that 20 mN/m). One method currently being investigated is the use of mixed surfactant systems, which can perform as well as some "superwetters" (silicone surfactants) and which are also more economically viable than such surfactant formulations. The task that remains is to develop ways to incorporate this technology into a commercial product (such as a fabric conditioner) to minimize the RMC of laundry.

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