Saving Energy and Time in Drying of Laundry: Molecular Mechanisms to Decrease the Residual Water Content of Fabric at the End of the Washing Cycle

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Saving of energy and time in drying of laundry directly depends upon the residual water content of the fabric at the end of the spinning cycle. If the amount of water left in the fabric is significantly reduced then the time and energy required to dry the fabric is less. Both these factors benefit the consumer and the national energy consumption. For the USA alone, the 30 % reduction in the residual water content of the laundry is equivalent of saving of 900 million dollars in the energy cost in addition to the saving of time for the consumer.

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We have shown that the residual content of water in the laundry after the spinning cycle directly depends on the surface tension at the air/water interface due to capillary force exerted by the meniscus in the fabric/water interface; higher the surface tension, higher is the residual water content of the laundry. Thus, by reducing the surface tension of residual water in the fabric, one can reduce the residual water content of the fabric after the spinning cycle. Thus, there is an obvious need for identifying the surfactants or their combinations to cause the maximum reduction in the surface tension of water trapped in the fabric. Of course, it is a challenging task to accomplish this objective without compromising the other parameters of the cleaning performance.

Using Sodium Dodecyl Sulfate (SDS), we have shown that there is a peak in the Residual Moisture (Water) Content of the fabric in the pre-CMC region, ~4 mM SDS concentration. There was a concomitant peak in the Dynamic Surface Tension (DST) at the same SDS concentration. The equilibrium surface tension did not show significant change in this SDS concentration range. A molecular mechanism was proposed to account for the peak in the DST in terms of a sudden cooperative adsorption of SDS molecules on the cotton surface in this pre-CMC concentration range of SDS. The results of some of these phenomena will be presented.

I. Introduction

The use of household laundry machines and dryers has become a necessity in the everyday life 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. Due to this lack of free time, consumer polls have shown that consumers want a significant reduction in the drying time of their laundry. In addition, the energy spent (and hence the time required) in drying fabrics depends on the residual

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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 US, such a 30% reduction of the RMC has the potential to save over $900 million dollars per year in energy cost as well as saving time for drying the laundry for the consumer.

The role of surface tension has been identified as a key aspect of the laundry process which has the potential to significantly alter the capillary height (as predicted by the LaPlace Equation). The reduction in surface tension can lead to a reduction in the residual moisture content [1]. It has been shown that the residual moisture content (RMC) of fabrics depends on the equilibrium surface tension of solution [1]. The LaPlace Equation for capillary rise (Equation 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 also decreases. Our rationale is that if the amount of residual water in fabrics can be reduced during the spin cycle of the washing machine, then that would correspond to a reduction in drying time during the drying cycle. This approach has also been shown by several other researchers in applications of dewatering of porous media or removal of liquids from porous media (oil recovery, dewatering of coal fines and dewatering of fabrics) [2-4]. However, it has been shown that for a pure surfactant system (in this case, SDS) there is a peak observed in the residual moisture content of fabrics before the CMC occurs. This sharp peak is believed to be due to a cooperative adsorption phenomenon of surfactant onto the fabric surface. Since our goal is to reduce the drying time of fabrics, it is important that during the laundry cycle that the concentration of the residual detergent from the wash cycle does not fall into the range of concentrations (i.e. the pre-CMC region) where the RMC increases.

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

It has been shown by Preston et al. that water is retained in moist fibers by capillary water held in spaces between fibers and by hydrates of the fiber molecules [2]. They have shown that the amount of retained moisture in viscose and cellulose fibers is proportional to the surface tension of solution. However, their studies only showed the direct relationship between surface tension of solution and the residual moisture content of fiber systems. In our work, we are using a single surfactant in increasing concentration to vary the surface tension and measuring the RMC of consumer fabrics instead of bundle of individual fiber strands. In comparison, Preston used several different surfactants at a single concentration to show the relationship between surface tension and capillary height for fiber bundles.

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 an oil reservoir were eliminated or reduced by reducing the interfacial tensions [5].

Shah 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 [6]. 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 (i.e. a smaller area/molecule). Other researchers have reported this synergism for anionic/cationic [7], anionic/zwitterionic [8-10], cationic/zwitterionic [8], nonionic/zwitterionic [8], anionic/cationic-

gemini [11], anionic-gemini/zwitterionic [12], cationic-gemini/nonionic [13], and cationic-gemini/sugar surfactants [14]. These investigations suggest that properly engineered synergism in a surfactant system can help reduce the surface tension values to ca. 20 mN/m.

It was shown that the RMC of fabrics depends on several different variables such as centrifugation time, centrifugation speed, and surface tension of solution [1]. However, it has been observed that the RMC of fabrics does not completely correlate with the LaPlace equation as expected. Before the CMC of surfactant solution we investigated, there is a sharp peak in the RMC of fabrics in the pre-CMC region. It is proposed that this increase in RMC is due to the sudden adsorption of surfactant onto the fabric surface. Since it has been shown that cotton has a negative zeta potential one might think that an anionic surfactant would have minimal adsorption on a negatively charged surface [15-17]. However, there have been several papers showing that sodium dodecyl sulfate (SDS) and other anionic surfactants adsorb onto negatively charged surfaces such as coal fines, cotton and cellulose [3, 15, 18-20]. Also, it has been shown by Somasundaran et al. that adsorption isotherms can show up to four adsorption regions [21], one of them being a sudden increase in the adsorption due to cooperative adsorption of surfactant molecules, which may explain the peak found in the RMC curves observed in this study. If surfactant molecules suddenly adsorb cooperatively on the solid surface at a critical concentration, then it must cause a concomitant decrease in monomer concentration in the bulk solution as this happens in the pre-CMC region. Thus, a simple method to determine the monomer concentration below CMC is to measure the surface tension of the residual solution. For a given surfactant below its CMC, the surface tension is a measure of the free monomer concentration of surfactant in solution. However, if the change is surfactant monomer concentration is not very large then the equilibrium surface tension may not show a significant

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change. However, the dynamic surface tension may show it more strikingly as it combines the change in the monomer concentration with its diffusion to the interface from the bulk solution. If there is a sudden increase in adsorption on the fabric surface then there would be less free monomer available to adsorb on the new air-liquid interface of bubbles created during the dynamic surface tension measurement. This would thus lead to an increased dynamic surface tension (which should be an amplified measurement of the change in the equilibrium surface tension) that should correspond to the increase in RMC in the same surfactant concentration range.

II. Experimental Section

A. Materials. The sodium dodecyl sulfate used in these experiments was obtained from the Fisher Scientific Company. Several sets of experiments were performed using various commercial surfactants provided by the manufacturer (DeIonic 100-VLF, DeIonic LF60-MOD, and Dow Corning Q2-5211). 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.

Several different types of fabric were used in the experiments for residual moisture testing. The fabrics used were as follows: a Department of Energy (DOE) standard test fabric (a 50/50 blend of polyester and cotton), a 100% cotton Hanes T-shirt fabric and an 86/14 cotton/polyester terry cloth which were supplied by the Procter and Gamble Company.

B. Residual Moisture Content (RMC) Measurements. For measuring the residual moisture, each fabric sample was soaked for ten minutes in surfactant solution and then placed in a DuPont Instruments Sorvall RC-5B centrifuge at 1000 RPM (which corresponds to the force of a

household washing machine of ~90g) for ten minutes. The experimental apparatus used to hold the fabrics is shown in Figure 1. Our setup uses a centrifuge tube with a copper insert that 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 like how a modern washing machine is designed).
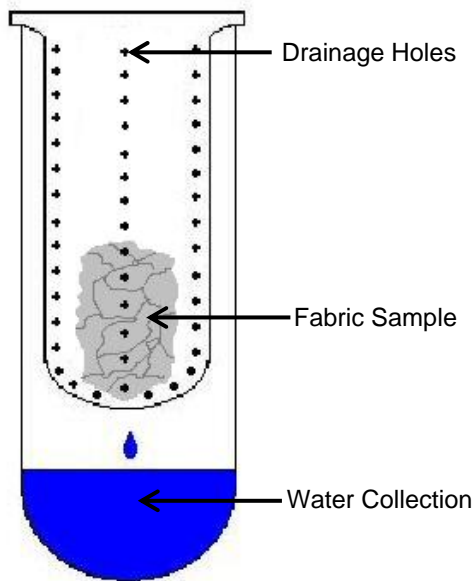

Figure 1: Experimental apparatus used to determine the residual moisture of fabrics.

After the fabric was soaked and centrifuged, the weight was then measured to determine the residual moisture content (RMC) as shown in Equation 2.

$$RMC\ \% = 100 * \frac{Weight_{centrifuged} - Weight_{dry}}{Weight_{dry}} \qquad (2)$$

C. Surface Tension Measurements. The equilibrium surface tension measurements were made using the Wilhelmy Plate method. The output from a gram-force sensor holding a platinum plate is sent to a transducer and then output to a voltage readout. The system was calibrated using

two known solutions (water and acetone at 72.5 and 23 mN/m respectively). The platinum plate was heated using a flame between each reading to remove surface contamination.

D. Dynamic Surface Tension Measurements. Dynamic surface tension was measured using the maximum bubble pressure technique. The pressure required to form a new bubble in solution is measured by a pressure transducer and the reading is transmitted to an oscilloscope. For these experiments, fabric was soaked in surfactant solutions for 45 minutes and the dynamic surface tension of the residual solution (in the presence of the fabric) was measured. All dynamic surface tension measurements were taken using an 18 gauge needle tip with a gas flow rate of 7.5 cm^3/min (which corresponds to 6-15 bubbles per second or approximately 66 to 166 milliseconds per bubble residence time at the needle tip). We chose this flow rate because at higher flow rates, the nitrogen gas forms a continuous jet in the surfactant solution at the needle tip. At lower flow rates, the results are similar to equilibrium surface tension results.

III. Results and Discussion

The first sets of experiments were performed to determine how the system reacts to different variables in the centrifugation process. As shown in Figure 2, the RMC decreased 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 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 (Figure 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 equilibrate, and all unbound water was able to be displaced from the fabric.
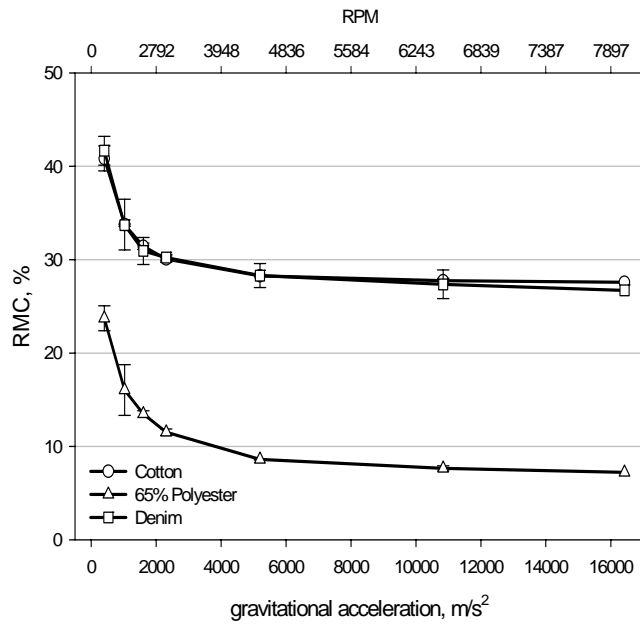

Figure 2: The effect of variation of the RPM on the residual moisture of several fabrics (Cotton, 65% Polyester and Denim).
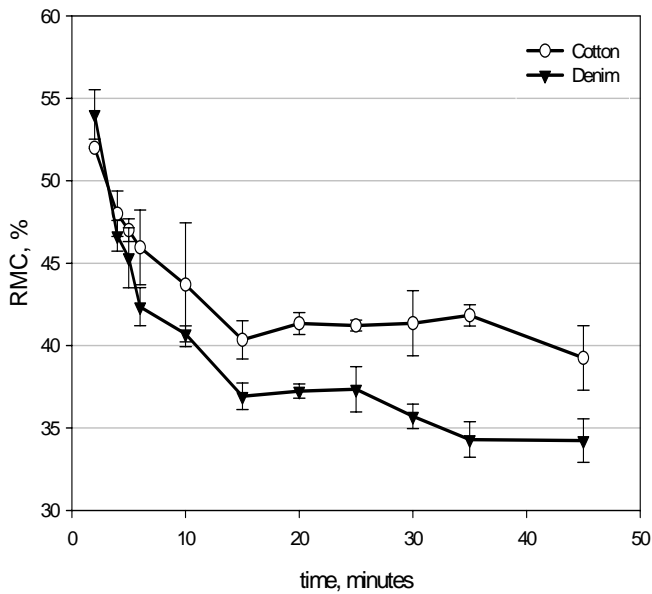
Figure 3: The effect of time variation on the RMC of Cotton and Denim fabrics.

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 Figure 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.

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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 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 as shown in Table 1) 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.
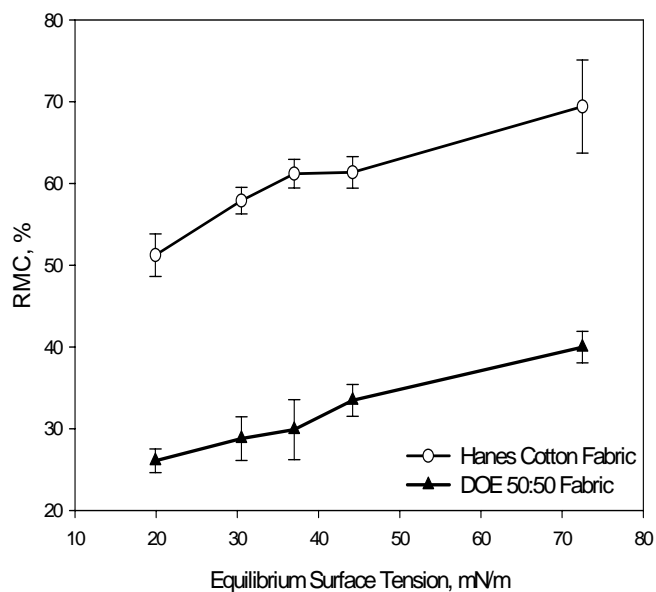
Figure 4: Relationship between RMC and surface tension for the detergent system for the Hanes and DOE fabrics at 1000 RPM (~92 times the force of gravity) centrifuged for 10 minutes.
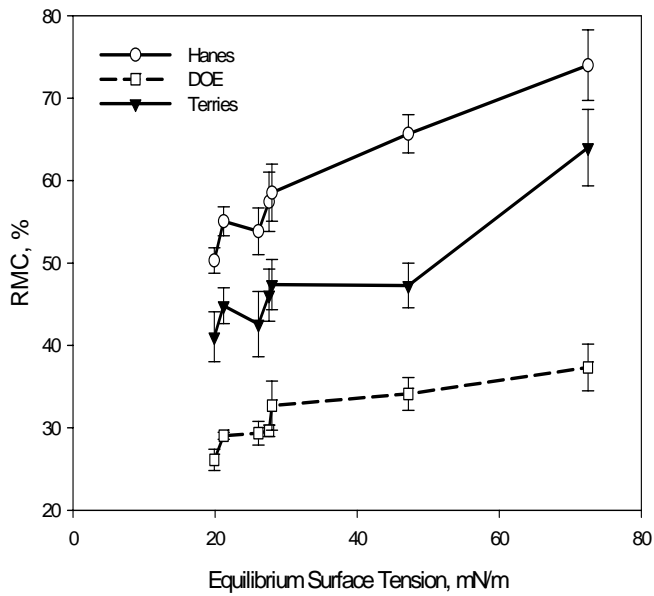
Figure 5: Relationship between RMC and surface tension for commercial surfactant systems for Hanes, DOE and Terry Cloth fabrics at 1000 RPM (~92 times the force of gravity) for 10 minutes.

Table 1: Surface tensions and corresponding RMC values for Hanes fabric for various commercially available surfactants.

	Surface Tension, mN/m	RMC, %
Water	72.5	74
Fabric Softener (0.1 wt%)	47.2	65.68
Leading Detergent (0.15 wt%)	30.5	58.53
DeIONIC 100-VLF (0.1 wt%)[1]	27.6	57.43
DeIONIC LF-60MOD (0.1 wt%)[1]	26.1	55.06
SDS:C12TAB (3:1 molecular ratio at 0.1 wt%)	21.2	53.84
Dow Corning Q2-5211 (0.1 wt%)[2]	19.9	50.3

[1] *Manufactured by DeForest Enterprises, Inc.*

[2] *Manufactured by Dow Corning*

We have shown that the RMC is indeed a function of the surface tension of solution. However, as shown in Figure 6, the residual moisture does not completely correlate to the equilibrium surface tension of pure SDS solutions in the range of 5-8 mM.
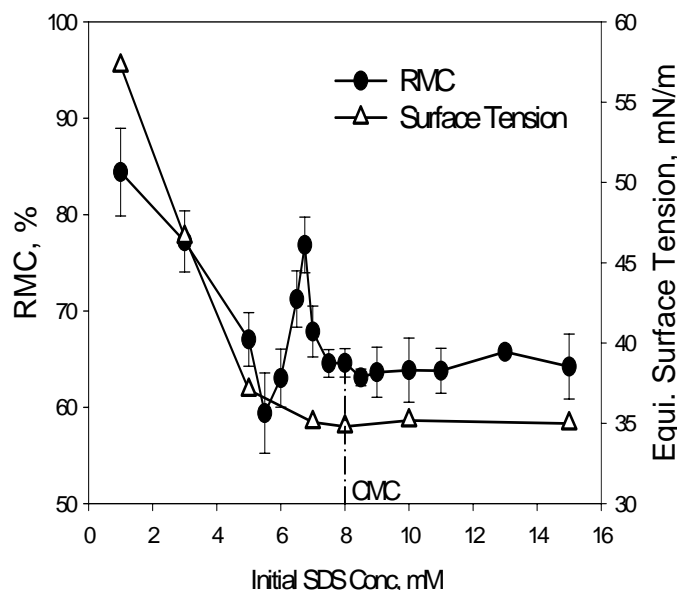

Figure 6: RMC of Hanes 100% cotton fabric as a function of SDS concentration plotted with equilibrium surface tension of pure SDS solutions.

It was shown that the RMC of fabrics did not completely correlate with the equilibrium surface tension of SDS as observed in Figure 6. Since it is believed that SDS is adsorbing onto the fabric surface, the equilibrium surface tension of the residual solution should show an increase in surface tension in the concentration range where SDS is adsorbing onto the fabric. The equilibrium and dynamic surface tensions of residual SDS solution were measured after allowing the fabrics to equilibrate for 45 minutes with the SDS solution. The fabrics were soaked in a 20:1 ratio of the volume of SDS solution to the weight of fabric. For each dynamic surface tension measurement, the nitrogen flow rate was held constant at 7.5 cm^3/min (approximately 6-15 bubbles per second). It is shown in Figure 7 that a small increase was found in the equilibrium

surface tension in the concentration range of 5-8 mM. Since there is a small decrease in free monomer in solution due to adsorption onto the fabric, the equilibrium surface tension shows a small increase. It was shown by the dynamic surface tension of the residual SDS solution (Figure 7), that the dynamic surface tension amplifies the small changes seen in the equilibrium surface tension. Since the lowering of surface tension is due to the diffusion of surfactant molecules to the air-liquid interface from the bulk solution (i.e. the lowering of surface tension is a time-dependant process), it is expected that the dynamic surface tension may amplify the changes seen in equilibrium surface tension. As shown in Figure 8, the increase in the equilibrium surface tension for the residual SDS solution corresponds with the increase of the RMC of the Hanes fabric presumably due to the adsorption of SDS onto the fabric surface.
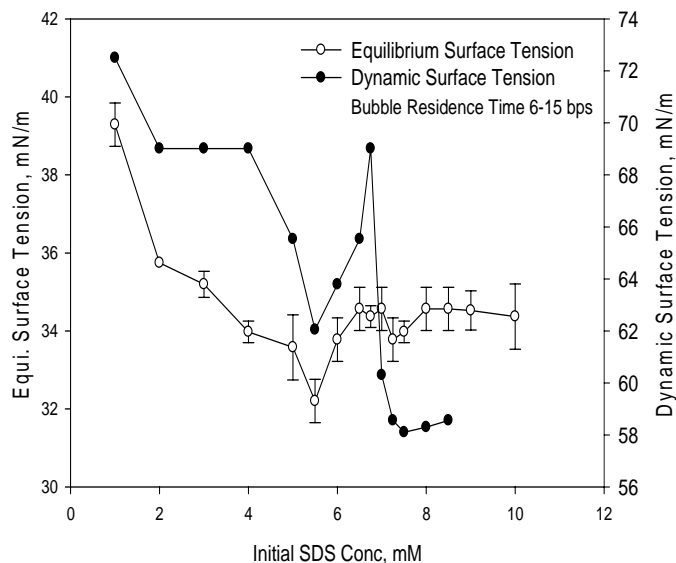
Figure 7: Equilibrium and dynamic surface tension of residual SDS solution after exposure to Hanes fabric.
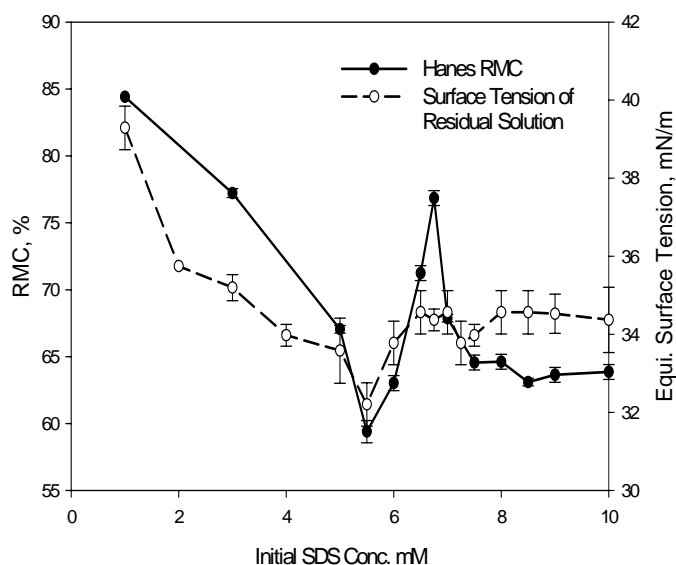
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Figure 8: Comparison of the RMC of Hanes fabric and the equilibrium surface tension of residual solution after soaking the fabric.

It has been shown that a peak exists in the RMC curve of Hanes fabric soaked in SDS solutions around approximately 7 mM SDS concentration. This peak has also been observed in the RMC of several other types of test fabrics of varying hydrophobicity as shown in Figure 9 (terry cloth and DOE fabrics with 14% polyester and 50% polyester respectively). As the fabric becomes more hydrophobic, the absolute RMC magnitude decreases as well as the magnitude of the RMC peaks as shown in Table 2. This decrease in the magnitude of the RMC peak may be due to the mechanism of adsorption onto the fabric surface (i.e. mainly hydrophobic interactions with more hydrophobic fabrics compared to hydrogen bonding with hydrophilic fabrics). The lowering of the RMC may be attributed to the increase in the contact angle of liquid with the fiber surface with more hydrophobic fabrics.
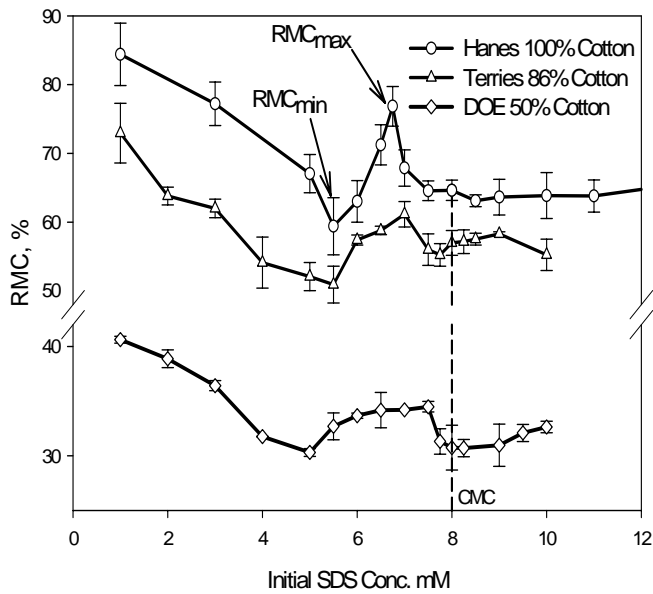
Figure 9: RMC of Hanes cotton fabric, terry cloth fabric and DOE test fabric as a function of SDS concentration.

Table 2: The magnitudes of the RMC peak for various fabrics for I) the absolute different in the maximum and minimum of the RMC peak, II) the difference in the maximum and minimum normalized with respect to the RMC maximum and III) the difference in the maximum and minimum normalized with respect to the RMC minimum.

	I	II	III
	$RMC_{max} - RMC_{min}$	$\dfrac{RMC_{max} - RMC_{min}}{RMC_{max}}$	$\dfrac{RMC_{max} - RMC_{min}}{RMC_{min}}$
Hanes	17.45%	22.72%	29.40%
Terries	10.23%	16.74%	20.01%
DOE	4.18%	12.13%	13.89%

We have shown in Figure 7 that there is an increase in the dynamic surface tension of the residual solution after the Hanes fabric was soaked. The dynamic surface tension was then

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measured for the remaining fabrics (DOE and terry cloth). Each fabric was soaked in SDS solutions allowed to equilibrate for 45 minutes. The dynamic surface tension of the residual solution was then measured (Figure 10, Figure 11 and Figure 12 for the Hanes, DOE and terry cloth fabric respectively). The flow rate was held constant at 7.5 cm^3/min (6-15 bubbles per second or approximately 66 to 166 milliseconds per bubble at the needle tip). It is shown in these graphs that a correlation exists between the peaks found in the RMC and the dynamic surface tension of residual solution. Since an increase in surface tension indicates low adsorption of surfactant at the newly created air-liquid interface in the residual solution, the peaks found in the dynamic surface tension measurements are believed to be indicative of surfactant adsorption onto the fabric surface.
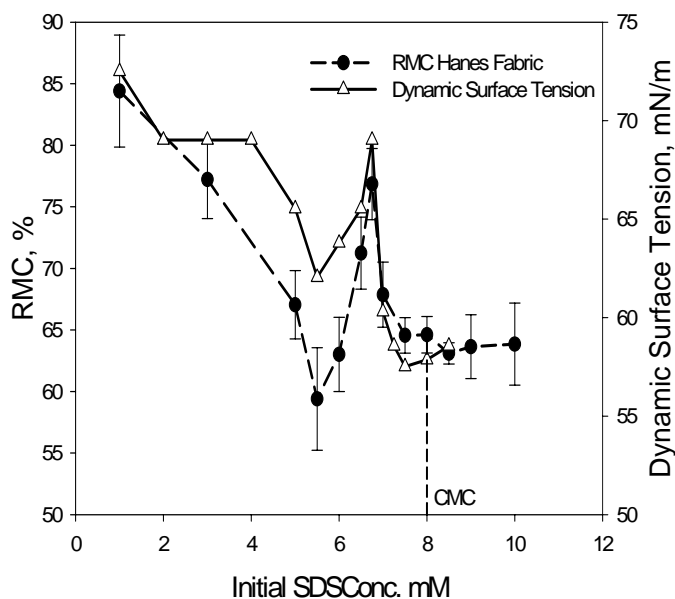

Figure 10: RMC and DST of the residual solution from the Hanes 100% cotton fabric soaked in SDS solutions.
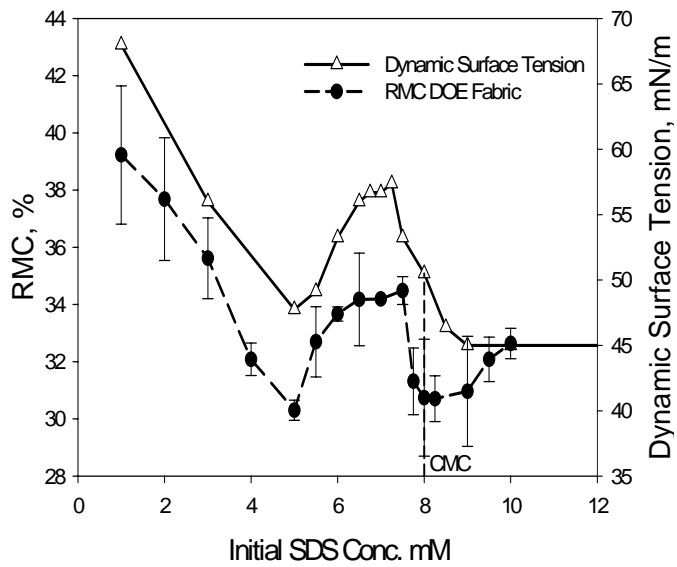
Figure 11: RMC and DST of the residual solution from DOE 50:50 cotton:polyester fabric soaked in SDS solutions.
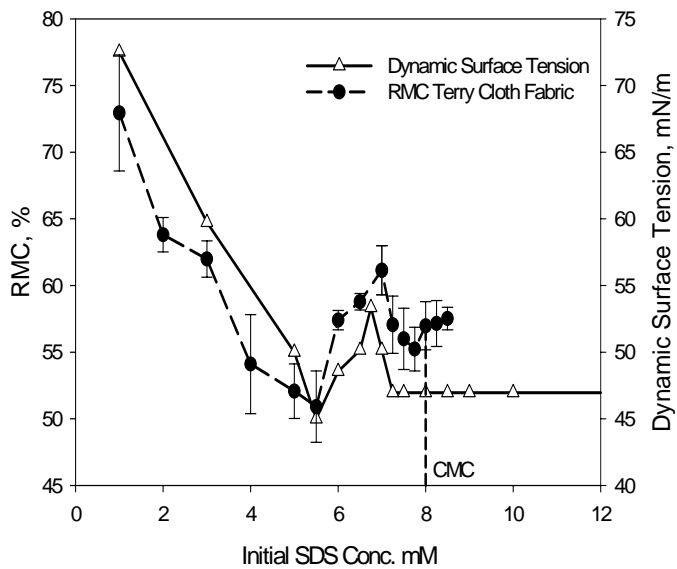

Figure 12: RMC and DST of residual solution from the Terry Cloth 86:14 cotton:polyester fabric soaked in SDS solutions.

An increase in dynamic surface tension is due to the reduced adsorption of surfactant at the air-liquid interface of the new bubble surface created during the measurement. We believe that the decrease in adsorption at the air-liquid interface is due to increased adsorption of SDS on the fabric surface. If there is increased adsorption of SDS onto the fabric surface due to cooperative adsorption, then it is assumed that there would also be a reduction in the free monomer concentration (which has been shown by the increase of equilibrium and dynamic surface tension of residual solution as shown in Figure 7).

It is shown in Figure 13 and Figure 14 the 4 regions associated with the increase in residual moisture content and dynamic surface tension due to of adsorption of SDS onto the fabric surface. Region A-B is the region of minimal surface adsorption of SDS onto the fabric surface. The decrease in RMC in this region is due to the increase of free surfactant monomer with low adsorption on the fabric surface. At a concentration of 5.5 mM of SDS, there is a minimum in the RMC and Region B-C begins. This region is due to the **sudden** increased adsorption of SDS onto the fabric surface due to a **cooperative adsorption phenomenon**. Due to electrostatic repulsion between the fabric surface and the SDS monomers, there is an opposition to adsorption. However, once several monomers adsorb onto the fabric surface, it provides and catalytic effect which increases SDS adsorption. This sudden increase in adsorption of the SDS onto the fabric surface reduces the free monomer concentration in the bulk solution thus leading to a reduced amount of free monomer in solution. Less monomer is available to adsorb onto the new air-liquid interface created during the dynamic surface tension measurement which leads to an increased dynamic surface tension. This increase in the dynamic surface tension leads to an increase in the residual moisture. At approximately a concentration of 6.75 mM of SDS, there is a maximum in the RMC where Region B-C ends and Region C-D begins. It is believed that at

this point, complete saturation of the fabric surface by the adsorption of SDS has occurred. Once maximum adsorption has been reached, any additional SDS added into the system will result in an increase in the free monomer concentration. The increased free monomer concentration provides the new air-liquid interface with higher SDS adsorption thus reducing the dynamic surface tension. At approximately 7.5-8.0 mM concentration of SDS, Region C-D ends and Region D-E begins. This region occurs due to the bulk solution reaching the critical micelle concentration (CMC). At this point, the free monomer concentration is approximately constant. Since the free monomer concentration is now constant, the dynamic surface tension and residual moisture remain should remain constant as well.
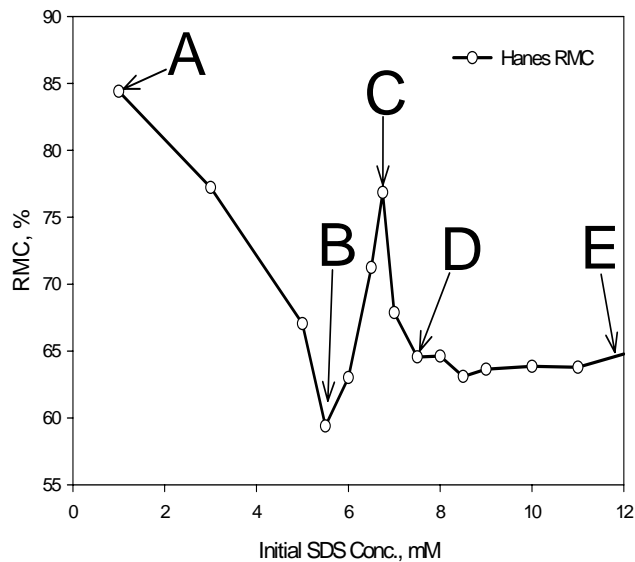

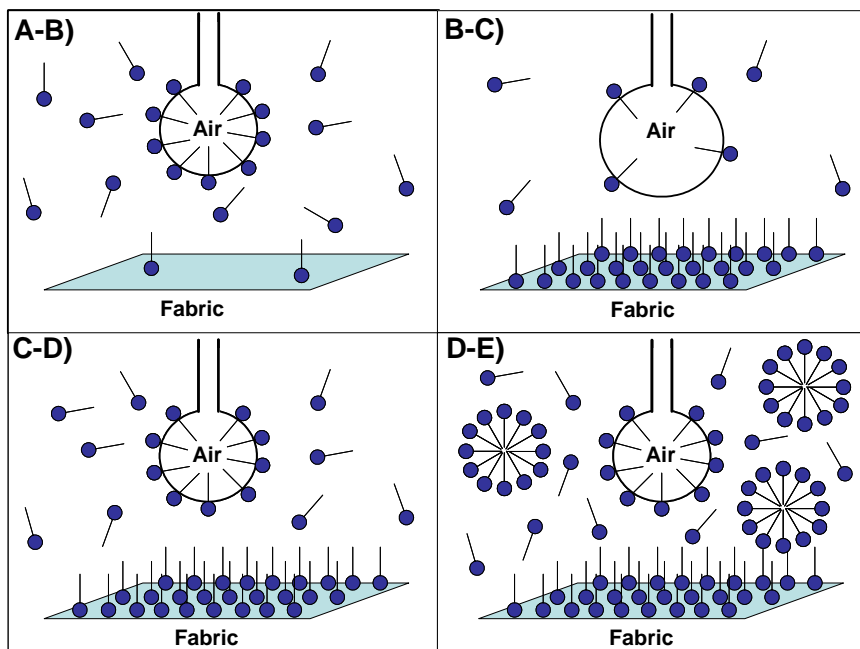Figure 13: Indication of the regions associated with the peak in the RMC of Hanes cotton fabric.

Figure 14: A-B) High adsorption of surfactant monomer at the air-liquid interface and low adsorption on the fabric-liquid interface resulting in a low dynamic surface tension B-C) Sudden adsorption due to cooperative adsorption on the fabric surface resulting in a decreased monomer concentration in the bulk solution and decreased adsorption at the air-liquid interface C-D) Maximum adsorption is reached at the fabric-liquid interface and increased adsorption is occurring at the air-liquid interface D-E) The CMC is reached and the monomer concentration is stable resulting in a constant dynamic surface tension and RMC.
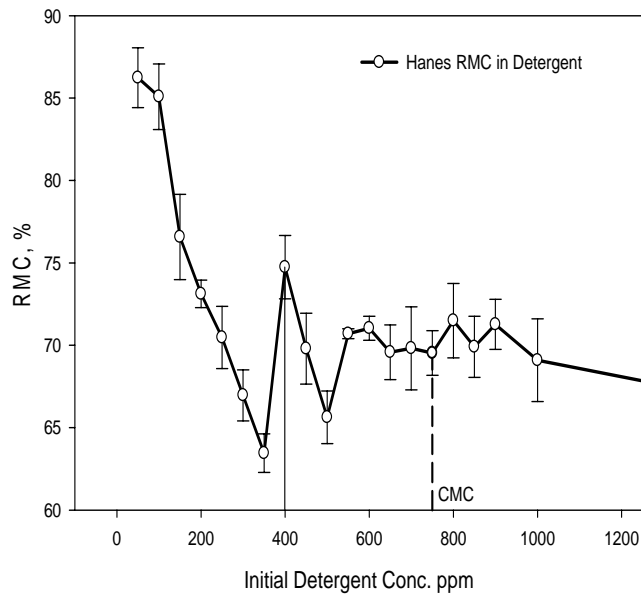
Figure 15: Residual moisture content Hanes cotton fabric soaked in a leading detergent.
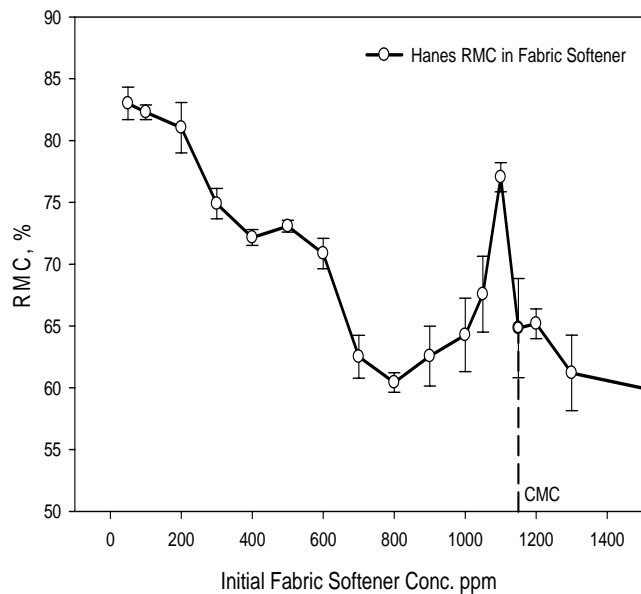

Figure 16: Residual moisture content Hanes cotton fabric soaked in a leading fabric softener.

It has been shown that there is a large increase in the RMC in the pre-CMC range for fabrics soaked in SDS solutions. We have proposed that this is due to sudden adsorption of the surfactant onto the fabric surface leading to a decrease in the effective monomer concentration

thus causing an increase in the surface tension. This increase in surface tension thus leads to a corresponding increase in the RMC. However, this peak was shown only for pure surfactant systems. In the laundry process, the use of complex surfactant systems is common. Since it has been shown that there is an increase in RMC due to adsorption for a pure surfactant system, a correlation must be made to determine if this same mechanism can be responsible for an increase in RMC in the same types of surfactant systems used in common household laundry products. As shown in Figure 15, there is indeed a peak found in the RMC of Hanes fabric before the CMC (determined by surface tension and dye solubilization methods) for a leading household detergent.

It was shown that there is an increase in the RMC for a leading detergent, however, it should be pointed out that this is not as important to the RMC after the final spin cycle since the wash cycle is followed by a rinse cycle where often a fabric softener is added. The final RMC is determined by the rinse water in the final rinse before the final spin cycle of the washing process. It is shown in Figure 16 that there is a peak found in the RMC of Hanes fabric soaked in a leading household fabric softener (this also occurs slightly before the CMC which is measured by similar techniques as the detergent). The results shown in Figure 16 were obtained by dipping the fabric in the fabric softener solutions without first washing the fabric with the leading detergent. Due to this increase in RMC in the fabric softener solutions, the concentration range where this increase is found should be avoided to lower the RMC and thus the time and energy required to dry the fabric. In the concentration range of 800-1200 ppm of the fabric softener, the RMC increases from approximately 60% to over 75%. The concentration of fabric softener in normal household use is approximately 500 ppm. This shows that if too much fabric softener is added in the rinse cycle that there can be a large increase in the RMC.

Over the years, the Shah research group has shown that the micellar relaxation time is a maximum at a concentration of 200 mM SDS [5, 22-26]. This maximum in micellar relaxation time has a dramatic effect on many different properties of SDS solutions (ranging from low foamability, high thin film stability, wetting time, oil solubilization, etc. Figure 17 and Figure 18). The Shah research group has also shown that micellar kinetics play an important role in detergency. Shah et al. has shown that the efficacy of removing non-polar compounds from fabrics has been shown to have a strong correlation with the relaxation time of micelles [22-27]. For example, it was shown by Oh and Shah that using 200 mM SDS (which was shown to have the longest micellar relaxation time in the SDS concentration range [23]) provided the most efficient removal of an artificial stain created by the solubilization of Orange OT in ethanol [26].
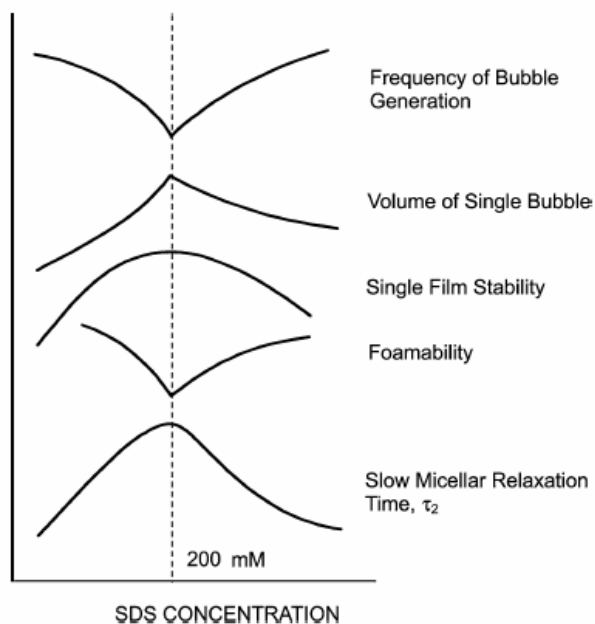

Figure 17: Liquid/gas phenomena exhibiting minima and maxima at 200 mM SDS concentration [23].
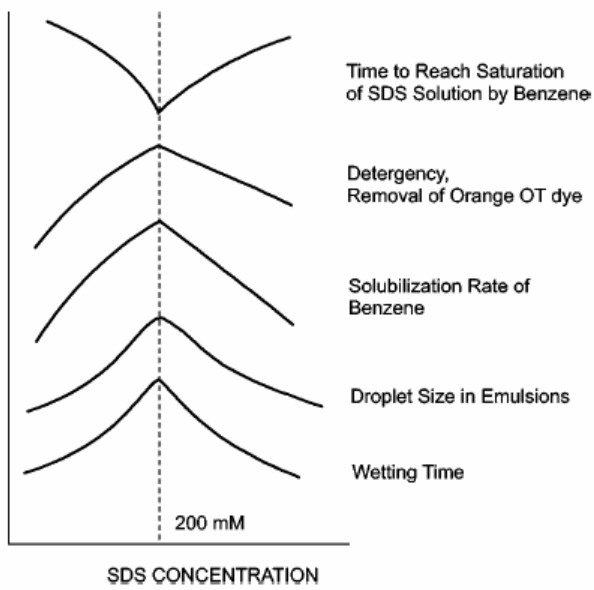
Figure 18: Liquid/liquid and solid/liquid phenomena exhibiting minima and maxima at 200 mM SDS concentration [23].

Since the relaxation time of surfactants play such a large role in many different properties of surfactant systems, the RMC of Hanes fabric around the concentration range of highest micellar stability was measured. Since the dynamic surface tension is related to the micellar stability (i.e. higher micellar stability leads to higher dynamic surface tension Figure 19), it would be expected that there will be an increase in the RMC around a SDS concentration of 200 mM. In Figure 20, we have shown that at 200 mM concentration of SDS that there is another maximum in the RMC of Hanes fabric. This maximum is believed to be due to the long relaxation time of the SDS micelles at 200 mM. The long relaxation time of the micelles would lead to a decreased monomer flux from the micelles to the bulk. This decrease in monomer flux would then be shown as an increase in the dynamic surface tension this leading to an increase in the RMC (shown in Figure 19). Alternatively, another possible explanation to explain the increase in RMC at 200 mM concentrations of SDS could be due to stabilization of thick films on the fabric

surface as well as the interfiber spaces due to relatively stable micelles. It has been shown by Shah et al. [28, 29] and Wasan et al. [30-35] that layering of micelles or particles can stabilize thin films (which could possibly explain an increase in the RMC).
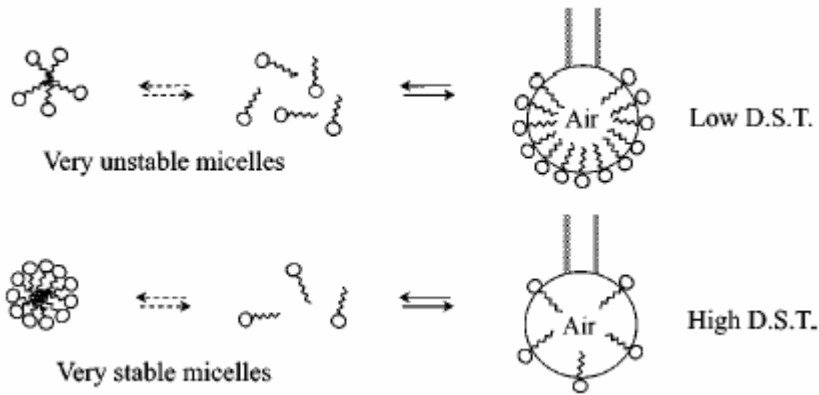

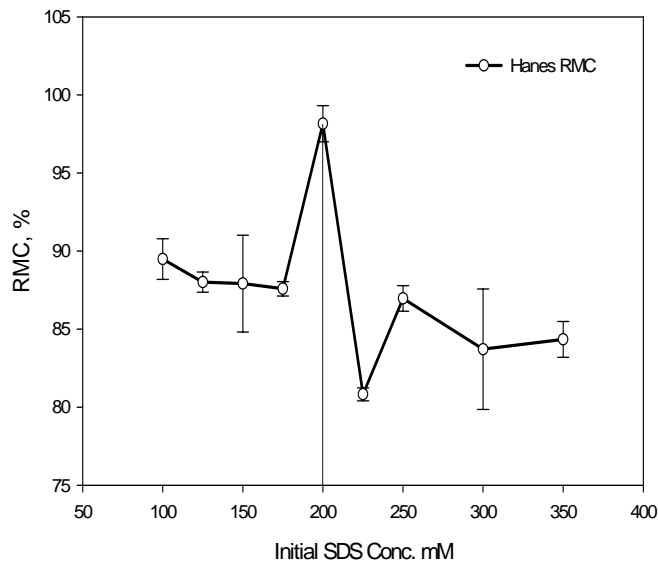Figure 19: Effect of micellar stability on dynamic surface tension.

Figure 20: RMC of Hanes fabric around the concentration range of most stable micelles of SDS (200 mM) (i.e. stable micelles can increase the RMC from ~80% to ~100% in SDS solutions).

We have shown that many different factors affect the RMC of fabric/surfactant systems. It was shown that adsorption phenomena are also an important factor in laundry processes. It should

also be noted that the dynamic surface tension seems to play a large role in the reduction of RMC of fabrics. If the rate of adsorption and micellar kinetics can be controlled, the magnitude of the RMC can be significantly altered (i.e. increased relaxation times for increased RMC or decreased relaxation times for lower RMC). In order to fully understand the increase found in the dynamic surface tension of residual solution and the RMC of fabrics, adsorption studies need to be performed in order to show a correlation in increased adsorption of surfactant to the increase in dynamic surface tension and RMC.

IV. Acknowledgements

V. References

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VI. Biosketch

Professor Dinesh O. Shah is currently director of the Center for Surface Science and Engineering at the University of Florida. He was appointed the First Charles A. Stokes Professor of Chemical Engineering and Anesthesiology and has been teaching at the University of Florida since 1970. In 1999, Professor Shah was recognized as one of the top 1% of most recently cited

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