Surface Tension as a Controlled Variable in Mechanical Dishwashing

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Using a continuous, in-line, nondestructive technique based on the maximum bubble pressure method, the surface tension of the wash water in a mechanical dishwashing machine has been monitored. This technique has enabled surface tension to be used as a controlled variable, providing feedback to regulate the amount of surfactant added. Assuming the mechanical force of the water spray is adequate to remove bound soil from the dish surface, the food soil may be titrated against surfactant, providing an indirect indication as to when the dishes are clean. This technique also could be applied to a recirculated wash solution for in-place cleaning.

In spite of its significance to a wide variety of processing operations, surface tension has remained one of the most neglected physical parameters to be used as a control variable. This situation can be attributed to a number of factors. The forces involved in surface tension are relatively small, and variations in some of the other variables may interfere with its measurement. The surface tension of a pure liquid can be markedly affected by small quantities of solutes. Consequently, contamination of test equipment or test solution may alter the result.

Of the techniques available for the measurement of surface tension, the torsion balance, drop weight and capillary rise method all use delicate equipment which needs to be scrupulously clean prior to each determination. In contrast, the maximum bubble pressure method uses a relatively simple and robust apparatus. Furthermore, a new surface is created with each bubble, thereby eliminating problems due to surface contamination.

Miller and Meyer (1) review some of these methods and describe an automated instrument for determining surface tension. Their method, based on the maximum bubble pressure technique, requires a known constant hydrostatic pressure and cannot be used when the liquid level varies (as in a mechanical dishwasher).

Smith and Schlein (2) describe a differential technique based on the maximum bubble pressure method: two capillary tubes of known different diameters are immersed in the test solution and a gas is bubbled through them into the liquid. The theory of this method is discussed in depth by Sugden (3) and Cuny and Wolf (4). The surface tension (γ) can be calculated from the equation:

$$\gamma = A\Delta P + B\varrho_s + C\,\varrho_s^2/\gamma$$

Where:
$A = g\varrho_m/2\,(1/r_1 - 1/r_2)$
$B = g\{[(r_2 - r_1)/3-(t_1 - t_2)/2]/(1/r_1 - 1/r_2)\}$
$C = g^2\,[(r_2^3 - r_1^3)/24\,(1/r_1 - 1/r_2)]$

r_1 and r_2 are the radii of the narrow and wide tubes
t_1 and t_2 are the depths of their immersion
ΔP is the difference of the maximum bubble pressure between the two tubes
ϱ_s is the density of the solution
ϱ_m is the density of the manometer fluid.

Cuny & Wolf showed that the third term 'C' contributes less than 0.07% to the equation and can be neglected.

If the tubes are arranged such that:

$$(t_1 - t_2)/2 = (r_2 - r_1)/3$$

then the second term becomes zero and also can be ignored.

The maximum difference between the back pressures of the two 'bubbler' tubes is, therefore, a function of surface tension only, being unaffected by the density of the test solution, the depth of immersion of the two bubblers and low flow rates (5).

In mechanical dishwashing the basic process variables are mechanical force, temperature and detergent (type and concentration). Detergent is added to the dishwasher in one of two ways: either aliquots of detergent are added on a time basis, or detergent is added when the conductivity of the wash water falls below a pre-set level. While the control of temperature may be straightforward, the control of detergent concentration is more complex, the conductivity of the wash water being subject to a variety of influences.

Addition of surfactant to a pure liquid results in the lowering of the surface tension to a minimum at the critical concentration (CMC) and then slightly increasing and levelling off (6). Initially, surfactant molecules migrate to the surfaces, saturating them before micelles are formed in the bulk of the solution. If the role of surfactant in dishwashing is to lower the interfacial tension, thereby aiding wetting, then the concentration of surfactant which corresponds to the surface tension minimum at the CMC must be the most efficient and economical to use. Preston (7) showed the relationships between surfactant concentration and the physical properties of the solution (density, surface and interfacial tension, osmotic presure and detergency) were nonlinear, with a point of inflection occurring at the CMC. In the case of detergency the maximum is achieved at the CMC, after which it does not change.

Harris (8-11) described the interaction of surface active components in washing detergents with food soils and the dish surface. Because surfactants combine with food soils and newly exposed surfaces, it does not seem unreasonable to suggest titrating the food soil with detergent, using surface tension as the indicator. Moreover, if the mechanical force is adequate to remove all the soil from the dishes, then the rate of change of surface tension could be used as an indication of when the dishes were clean.

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MATERIALS AND METHODS

Lengths of stainless steel hypodermic tubing were fixed into a perspex block with an epoxy adhesive, using a travelling microscope (resolution 0.001 cm) to separate the ends by 1/3 the difference of their diameters. The larger tube was 2.0 mm i.d. and the smaller tube was 0.3 mm i.d. Separate channels of a peristaltic pump forced air into the two needle tubes immersed vertically in the test liquid. The back pressure from the two bubbler tubes was measured using the differential manometric pressure transducer described by Rosenthal and Thorne (12). This transducer was modified by incorporating integrating amplifiers into the circuit before the differential amplifier. These integrators were reset by a solid state switch controlled by a micro-computer which also was used to log data. A single fluid manometer was used with 10 ppm nigrosine in absolute alcohol as the fluid, and the cell length was 10 cm. The differential back pressures from the bubbler tubes were calibrated for solutions of known surface tension, 96% alcohol (22 dynes/cm) and distilled water (72 dynes/cm).

All titrations were carried out in an experimental washing machine. Distilled water was used throughout the experiments. The conductivity of the solution was measured. The temperature was measured with copper/constantan thermocouples and controlled by the computer by switching a 2.1 kW immersion heater.

A soil based on that of Hucker (13) was used. The recipe of the soil and method of preparation were: 10 g peanut butter, 10 g unsalted butter, 10 g lard, 10 g soft flour, 10 g dried whole egg, 15 g condensed milk, 50 ml water, 3 ml 1M sodium hydroxide and 4 ml India ink. The flour, egg, milk and water were mixed in a Waring blender; the peanut butter, lard and butter were melted and then blended into the mix; the sodium hydroxide and India ink were added last, and the food soil was blended at full speed for two min.

Two types of experiment were performed: titrations of food soil with organic surfactant, using a 2% aqueous solution of the surfactant KA880 (a synthetic fatty acid, ethylene oxide adjunct manufactured by Albright and Wilson Ltd.); and titrations using a built detergent consisting of a 10% aqueous solution of an inorganic builder mix (46% sodium tripolyphosphate, 30% sodium metasilicate, 15% sodium zincate and 1% carboxy methyl cellulose), plus 2% KA880. The unbuilt detergent titrations were to determine the feasibility of using the surface tension as an indicator, and the built detergent titrations were intended to simulate conditions of commercial dishwashing machines. In both cases the detergent was dispensed using a peristaltic pump controlled by the computer.

Temperature and surface tension were initially brought to beyond their set points of 50 C and 50 dynes/cm, then Hucker's food soil was added through a disposable syringe. During the experiments the temperature and surface tension were maintained beyond their set points by on/off control.

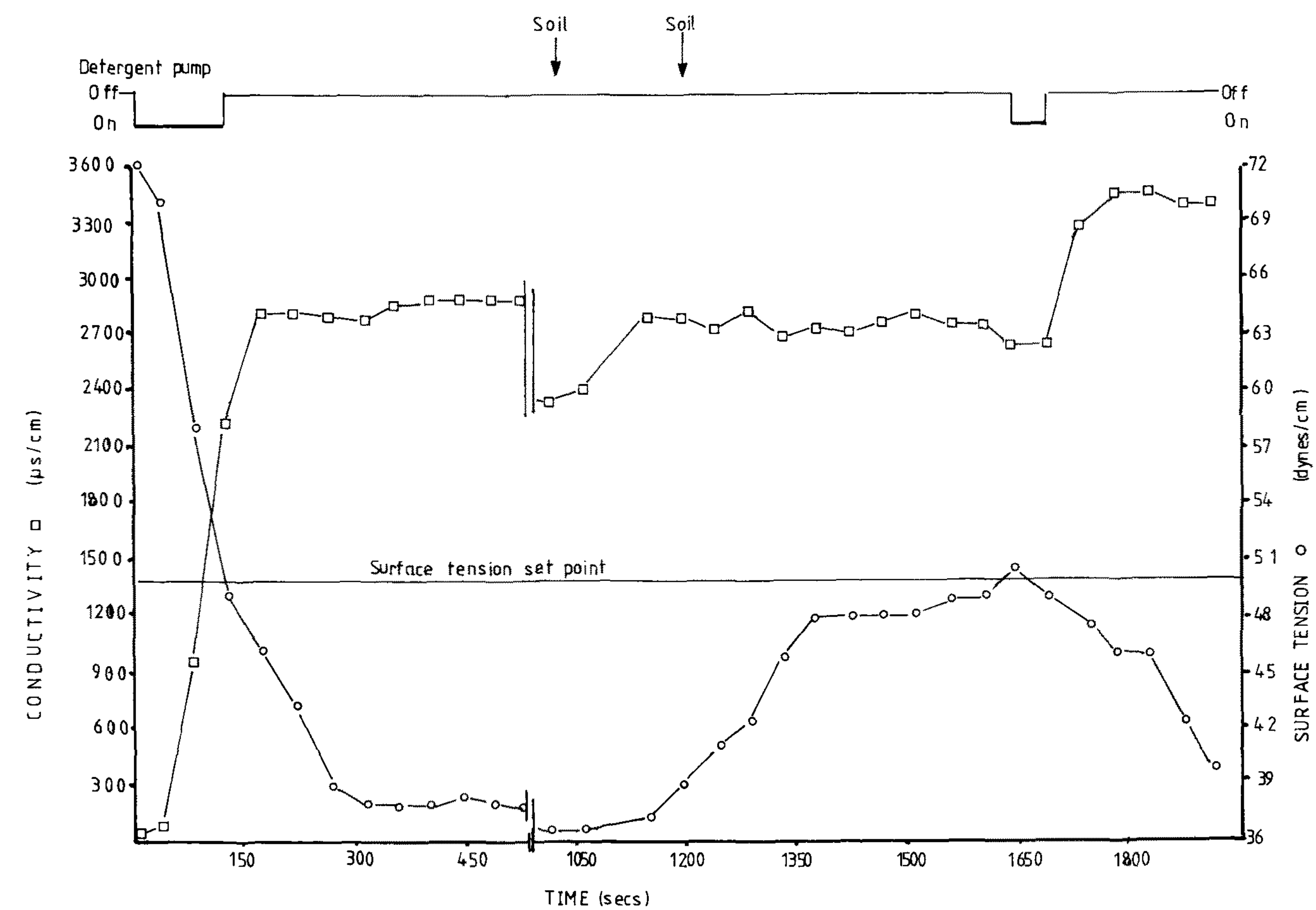

FIG. 1. Food soil titration with built detergent.

RESULTS

Figure 1 indicates the changes in surface tension and conductivity as: (i) built detergent is added to the washing machine, and (ii) food soil is added. The detergent pump was turned on for each sampling period with a surface tension at or above 50 dynes/cm.

Figure 2 shows four consecutive soil titrations using unbuilt detergent; the unit of time in all titrations is 15 seconds. The detergent pump was turned on for each sampling period with a surface tension at or above 50 dynes/cm.

DISCUSSION

While lowering the surface tension is of primary importance to dishwashing, it is not the only process involved in detergency. Lowering the interfacial tension will aid wetting, remove fats from surfaces by gradually displacing them, solubilize otherwise insoluble matter (14), and stabilize emulsions of suspended soils. The predominant components of dishwashing detergents, inorganic builders, are active cleaning agents in their own right: chelating cations to soften water, deflocculating colloids (15) and hydrolyzing fats and proteins (16).

The response to the addition of Hucker's food soil caused an increase in the surface tension in both types of experiment. As the surface tension rose through the set point, detergent addition recommenced, with a subsequent depression in the surface tension of the solution. This was accompanied by a rise in the conductivity of the solution. The conductivity was, in effect, an integral of the concentration of electrolyte added in the form of detergent plus soil.

Conductivity has been used to control the addition of detergent, but is not itself a measure of deterging power. It is not even a measure of available alkali or chelating agent concentration. Conductivity is easily measured and as such could be a useful indication of the rate of dilution (many commercial dishwashing machines continuously replace wash water with spent rinse water while allowing the wash tank to overflow down the drain). In contrast to conductivity, the surface tension does indicate the potential deterging capacity of the solution.

A model could be conceived in which soiled dishes were introduced to an open-loop dishwashing machine, whose wash water was initially at the CMC of the detergent used. Assuming the water spray was adequate to reduce the bound soil to an acceptable level, one would expect the surface tension of the wash water to rise and then level off to a new constant value. If the model described above used the signal from the surface tension sensor as feedback to control the addition of surfactant (thereby maintaining the CMC), one would experience a rapid initial addition decreasing until no further detergent was added, at which point we could assume the dishes were clean.

Any lag introduced by the response time of the sensor would merely offset the detection of a change in surface tension. The cleaning process would therefore precede the detection of a change in the surface tension such that when no further change in the surface tension was detected, the dishes would have been cleaned for an additional period after they were already clean.

Dispensing detergent based on surface tension need not be limited to mechanical dishwashing; it could be applied to the recirculated wash solution in cleaning in-place. In addition to revealing when the surfaces are clean, monitoring the surface tension may have other

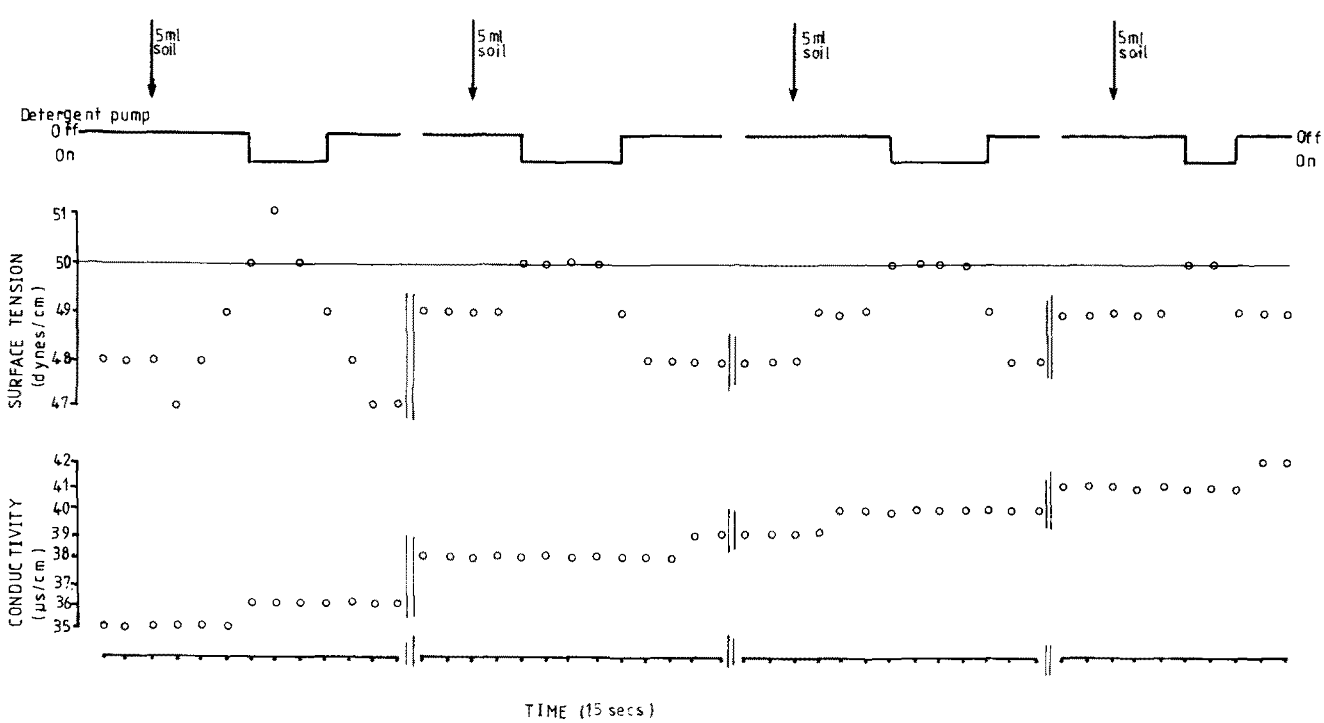

FIG. 2. Food soil titration with unbuilt detergent.

benefits. If the surface tension could be maintained close to the CMC minimum, it would eliminate excessive use of detergent, thereby reducing the cost of chemicals and making the process more efficient. Controlling the addition of surfactant also could be of benefit to the wastewater treatment system. Nonionic surfactants have proved troublesome, causing foam, while raised levels of phosphate in sewage have caused concern due to fears of eutrophication (17).

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