REPORT

Clean development and demonstration – Sustainable domestic washing - s'wash

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Preface

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Summary

S'wash is an idea grant support project sponsored by MISTRA to create innovative research projects with great potential to improve the environment. S´wash has decreased the water usage down to a consumption of 10.3 litres of water for a washing load of three kilograms of textiles, a decrease of 79 percent compared to the standard washing machine used in European households today. During the course of the project a lot of different techniques and approaches have been tested to find suitable solution to implement in a washing machine. Two prototypes have been built to evaluate solutions and ideas. The prototypes are based on standard washing machines but the solutions are not yet ready for production.

Sammanfattning

S´wash är ett idestödsprojekt finansierat av MISTRA, ett finansieringsstöd för att skapa innovativa forskningsprojekt med stor potential att förbättra miljön. S´wash har minskat vattenförbrukningen ned till endast 10,3 liter för en tvätt med tre kilos smutstvätt, en minskning med 79 procent jämfört med standardtvättmaskiner som används i de europeiska hushållen idag. Under projektets gång har ett stort antal tekniker och lösningar utvärderats för att finna lämpliga sätt att implementera dessa i en tvättmaskin. Två stycken prototyper byggdes av Asko och Electrolux för att utvärdera framtagna lösningar och idéer. Prototyperna baserades på standardtvättmaskiner men lösningarna är ännu inte redo för att tas in i produktion.

Background

Water resources are limited in many developing countries. Increased living standard brings a rapid increase in water use due to water flushed toilets, personal hygiene and washing of textiles. The development of new techniques to minimise the use of primary water resources or the near-to-contamination-source clean-up techniques, will urgently be needed. This project focuses on one of the areas of extensive water use; Washing!

Textiles need a certain degree of wetness which differs between different fabrics but 200 percent of cargo weight in water is usually necessary. This implies that a wash cycle for a load of three kilograms of textiles with three rinses consumes at least 24 liters of water. However, a more realistic value for a typical European machine is 45 liters of water.

Excessive use of detergents is always present. The amount needed when washing with a compact detergent is approximately half the amount compared to non-compact detergent (i.e. with sodium salts included). This has increased the risk for overdosing. The detergents today are much more concentrated, which means that when someone puts a little extra in the detergent dispenser, the overdosing will have a larger impact than ten years ago. The dose-recommendations on the back of the package relate the dosage to the hardness of the water. Since the recommended dosage are described in intervals, for example soft water, 0-

6 °dH, a person with a water hardness of 2 °dH will end up overdosing even though following the instructions.

Consumers tend to wash several items separately, or with a very few other items. This behaviour is enhanced by the clothing-manufacturers' recommendations to “wash separately”. The average domestic washing load in Europe is far less than three kg. This is a direct contradiction to the present trend of producing domestic washing machines with a load capacity of up to eight kg. Moreover the surfactants in a normal household detergent are acutely toxic for aquatic systems, due to their reducing effect of the surface tension. Additionally, the phosphate used in the detergent is a nutrient which causes blooming of algae in lakes and seas, which is a problem of great concern in many areas of the world. Thus overdosing and low textile loads that lead to frequent washing present environmental problems.

Since several years the EC-countries have had a goal[1] to reduce the electricity and water consumption. Today a normal wash with three kg (cotton) with a horizontal axis washing machine uses approximately 0.75 kWh where 80% is used for heating the water. In some parts of the world (USA, Asia) the use of agitator machines (vertical axis washing machines) is frequent. These machines use higher amount of water compared to the horizontal axis machines and often use the hot water supply in the building. There is a European labelling of household white goods where the suppliers have to state the energy and water consumption. The amount of fresh water is decreasing and to use drinking-quality water in the toilet and to wash, will soon be a non-accepted luxury.

The R&D today, both within industrial and domestic washing, is heading towards low temperature washing with combined chemo-thermal disinfection. Enzymes with larger process windows and multifunctional ingredients as well as new bleaching agents are definitely on the agenda. Sanyo launched a washing machine 2002 that they claimed needed no detergent, but since the ability to clean was the same as hand-wash without detergents this machine became popular solely in Japan. In 2007 Samsung launched a washing machine that uses silver ions for disinfection, but so far with a limited success due to the environmental issues concerning silver ions. Miele launched 2006 a domestic machine with a detergent dosage system. Today there are several producers of washing machines that offer automatic dosage systems.

Hans Rosling shows on statistics in his speech[2] about the “Magic Washing Machine” that only one out of seven billion people have access to a washing machine. The rest of the population washes by hand which is not efficient in a water consumption perspective.

Goals

The objective of this project was to physically design and run a washing machine prototype which, compared to current machine standards, would prove the ability to

- reduce freshwater use with at least 70 percent
- bring a significant reduction in environmental impact of detergents used
- reduce electricity use with at least 60 percent
- maintain the cleaning quality

Organization

S'wash was assembled with the competences necessary to reach the objectives of more environmental friendly domestic washing. Chalmers has state-of-the-art knowledge regarding detergents and nanotechnology. The institutes IVL, IFP and IMEGO are experts in the fields of optimization, environmental analysis, sensors and washing processes. The industrial partners Unilever, Akzo Nobel, ASKO Appliances and Electrolux perform R&D and manufactures detergents and washing machines.

The S'wash R&D work was carried out in five work packages (WP), each addressing a specific topic of concern.

- WP1 – Water and energy
- WP2 – Bacterial growth
- WP3 – Detergents
- WP4 – Sensors
- WP5 – Environmental

The following sections contain a brief description of each WP and its main results. More detailed information is reported in the corresponding appendices.

WP1 – Water and Energy

Washing machines use a considerable amount of water. Despite new technical improvements producers are on the verge of what is possible when it comes to reducing water use. There is therefore a need for a technical leap to see what could be done without having the boundaries of technical enhancements following the normal product development. One prerequisite is still valid and needs to be fulfilled and that is that textiles needs a wetting of approximately 200 percent for both wash and rinse steps for maintaining cleaning performance and avoid residues after rinse.

The problem

WP 1 contains the central development in the project. It deals with minimizing the water usage with 70 percent and energy with 60 percent during household washing of clothes.

Results

To save water different possibilities and techniques has been evaluated theoretically but also through washing with prototype washing machines constructed especially for S´wash. The evaluation criteria's used for the different techniques are; performance, if it is practically possible and which consequences it has on other goals in the project.

The conclusion drawn is that prototypes with three tanks for storing water and a temperature of 30 °C is a good compromise between saving water and energy and cleaning performance, see Figure 1 for overview. The reason not going below 30 °C is to keep the important solubility for stearin like detergents and allow temperature as a helping factor when cleaning.

Figure 1: In the illustration the four steps in S'wash wash cycle are explained. The washing machine is loaded with dirty laundry and detergent which is automatically dosed. The main wash is performed at 30 degrees Celsius with water from the first rinse in the previous wash cycle. The wash water is too dirty to store and is therefore sent to the sewage. The first rinse is performed with water from the second rinse from the previous wash cycle and the second rinse is performed with water from the third rinse from previous wash cycle and the third and last rinse is performed by tap water. The water from the three rinses is stored for use in next wash cycle in separate tanks.

Dismissed techniques include:

- Membrane filtration for recycling water internally due to its size and energy consumption
- Heat exchangers due to that the temperature used is fairly low and that small change in temperature is hard to store until next wash cycle
- Air/Water heat exchangers due to its size and that it would take long time to do it efficiently and the heat needed in a washing machine is in the first step of the cycle

To achieve good cleaning performance you need to compromise between temperature, chemistry, time and mechanical work. You need all of the parameters to sustain a good cleaning performance but you have some freedom in changing the relationship between them. For example lowering the temperature needs to be compensated for by better detergent formulations, heavier mechanical work and longer washing time. This is in literature described as the Sinners circle.

Two prototypes, one by Asko Appliances and one by Electrolux, were built as a proof-of-concept of the S'wash washing cycle, see Figure 22. The prototypes were evaluated with regards to:

- Water and energy consumption to see if the goals of 70 percent less water and 60 percent less energy consumption are reached.
- Electrolytic concentration in the different tanks to see if we have an accumulated amount of electrolytes due to carry over effects.
- Bacteria concentration over time in tanks and also in textiles.
- Colour transfer and greying between washes.
- Washing performance for a wide variety of different detergents, temperatures and washing times.

Figure 2. S´wash prototype washing mashine (the Electrolux prototype).

Table 1. Performance summary for the prototype compared to a typical household washing machine.

	Water (l/kg load)	Energy (kWh/kg load)	Wash Performance	Staining	Greying
Prototype	3,4	0,083*	F	1,7	-0,8****
Reference	16	0,35**	C***	N/A	N/A

* 30°C, ** 60°C, *** Electrolux based prototype, **** After 4 wash cycles with IEC-A

The goal was reached and surpassed for both water and energy savings with 79 percent reduction of water usage and 76 percent less energy usage, see Table 1. Saving water does not affect the cleaning performance over multiple washing cycles (see appendix WP1 – A2) since the carry over effect is small and quickly finds its equilibrium.

There is a slight visible staining on white cotton when this is washed in the rinse water from a previous wash with new unwashed blue jeans (see appendix WP1 – A4). The staining decreases in the second wash but are still detectable. This is a worst case scenario and the sensors in WP4 address this problem together with detergent formulations in WP3. Greying can be solved by detergent formulation, it is seen that for IEC-A reference detergent there are no big issue with greying but with S'wash L3 formulation and a commercial liquid detergent we have visible greying after multiple washes (see appendix WP1 – A2).

When going from 60°C to 30°C the cleaning performance decreases which is not surprising since temperature is such an important cleaning factor, we did not reach the goal of keeping the same cleaning performance as for a 60°C wash but got a cleaning performance of F. Grade F corresponds to grade 4 in the former rating scale from the Swedish Board of Consumers (see appendix WP1 – A3 for more information).

Future challenges

- To make smaller water footprint pre-processed grey water from other sources in the home, i.e. bathtub, hand wash and shower, could be used as cleaning water.
- Collaborate with companies that perform installations in laundry houses or other bigger installations where you can address the problem more effectively through having connected several washing machines. You could for example have separate storage tanks for storing coloured laundry washes.
- Finding alternative to lower the energy consumption, i.e. connect district heating or hot water from tap. Only lowering the temperature needs more efficient detergents. There is a lot of research developing new low temperature detergents so soon there is hopefully some that can perform well.

WP2 – Bacterial growth

The problem

The great challenge for preventing bacterial growth and avoid health problems and bad odour was clear from the beginning of the project. The human body and soil, water and air surrounding us all contain bacteria which naturally exist in the environment. When clothes are being used they will consequently also be exposed to microorganisms. In a wash cycle, the water removes microorganisms from the textiles and is thereafter flushed into the sewage and treated further in a municipal sewage plant. In the S'wash machine the "contaminated" rinse water will be stored in the water storage tanks until the next wash cycle takes place. An accumulation of microorganisms and biofilm formation in the water storage tanks must be prevented.

Results

Bacteria

The Swedish Environmental Protection Agency has set up general guidelines for bathing water, see Table 2.

Table 2. Bathing water guidelines

	Guidelines (CFU/100ml)	
	Inland water	Coastal water
Intestinal enterococcus	400	200
E. coli	1 000	500

Guidelines for the usage of grey water in Sweden are currently not available. Grey water is more commonly used in countries where a shortage of water exists, but we have not found guidelines regarding limit values for these countries either. The values for bathing water signify a good water quality and should therefore also work as guidelines for water for laundry.

An extended test was performed to determine the amount of colony forming units (CFU) that exists in normal domestic rinse water. Microbial cultures were made on rinse water 1 and 24 hours after the wash cycle to find out the presence of microorganisms directly after wash and the magnitude of the growth over time.

After being in contact with AkLab, SIK and Vattenverket it was decided to look for the total amount of colony forming units and individual microorganisms that possibly and probably would be present in the water. Several microorganisms in addition to Intestinal enterococcus and E. coli were included in the test (see appendix WP2 – A3).

The result showed that the amounts of colony forming units were high in rinse water right from the beginning. It is therefore obvious that an active technique will be needed to prevent further bacterial growth. After 24 hours, the number of microorganisms increased dramatically. The guidelines set up for bathwater has been fulfilled regarding E.coli directly after the wash cycle. The numbers of intestinal enterococcus/100 ml are however above the guidelines for both inland and coastal water.

A test was performed when fabrics were washed in the prototype machine (appendix WP2 – A5). Even though the amount of CFU/ml increased in the water storage tanks, the fabrics had the same amounts of CFU/dm^2 after wash in fresh water and wash in highly contaminated water. This indicates that clothes do not seem to get affected even if the contamination level of the water increases over time, but more tests needs to be performed for validation.

Active techniques

There are several available techniques already in use for inhibiting bacterial growth and biofilm formation. Economical, toxic and environmental aspects have been taken into consideration regarding all techniques when they have been discussed in the work package. Normally distilled water is treated to get a completely bacteria free water system. Methods for cleaning heavily soiled grey water are not as common however.

Ultrasound was a very interesting solution initially, but was later on excluded from the project because of the high price and the large equipment needed. The technique is still interesting but not fully accommodated for this application as yet.

UV light alone is not effective for heavily soiled water and for removing biofilm. It needs to be used in combination with for example water filters. A large disadvantage is that the lamp needs to be controlled, washed and exchanged regularly. One aim of the project has been to develop a machine which needs minimum maintenance. This technique needs to be developed towards very low maintenance to work in this system. This is not feasible within the time frame of this project.

According to the literature screening (see appendix WP2 – A1), surfaces can have an influence on biofilm formation. The rate of contamination is slowed down on smooth surfaces (compared to rough ones) in the initial stages of microbial attachment. Different surfaces were evaluated in the project in order to choose a material for the water storage tanks. If biofilm is formed in the tanks, it will be an even greater challenge to keep the bacterial growth in the water under control since biofilm is harder to affect and remove than free-floating organisms in the water. Unfortunately surface treatment showed no influence on the biofilm formation in the screening test (see appendix WP2 – A2).

Silver coating of surfaces are common antibacterial treatment to prevent microbial growth but was excluded due to environmental aspects.

Filters were used for removing larger particles and fibres throughout the project but turned out to be problematic. The filters were filled after only one or two washes and needed to be cleaned. A technique for automatic cleaning or change of filters needs to be developed if filters are to be incorporated in the final washing machine. Asko did not use a filter in their prototype machine and had no problems with fibres and particles. Filters were however needed in the Electrolux prototype to avoid problems with the valves, which did not entirely close due to gathering of fibres and residues.

It was early decided to use a biocide to inhibit bacterial growth in the water storage tanks. After recommendations from AkzoNobel, Triameen Y12D-30, an amin based biodegradable biocide with cationic properties in certain environments, was chosen for further work. It was also decided to test hypochlorite, with a well-known bactericidal effect. Due to the bleaching properties of hypochlorite, a test regarding colour fastness properties was also performed.

The results showed that the bacterial growth is inhibited with Triameen Y12D-30 and hypochlorite when sufficient concentrations are being used. Hypochlorite was however excluded from the project due to its bleaching properties. Triameen Y12D-30 kept the bacteria under control for 6 days when dosed at a concentration of 100 ppm ppm (see appendix WP2 – A6).

Triameen Y12D-30 was further tested in the ASKO prototype machine. The test showed that it can be an efficient bactericide for reduction of bacterial growth. The water had low numbers of colony forming units when it entered the washing machine (see appendix WP 2 - A7).

Compatibility tests performed with Trimeen Y12D-30 and the S'wash detergent L3 showed that this biocide was not compatible with the anionic surfactants in the S'wash formulation. The biocide also tends to adhere to textiles and other surfaces. An alternative biocide with lower affinity compatible with the detergent was therefore tested; Sodium dimethyldithiocarbamate solution recommended of AkzoNobel. The additional bactericide was evaluated in the ELS prototype machine. Sodium dimethyldithiocarbamate did however not have any effects at all in on the bacterial growth in the rinse water, at a concentration of 100 ppm (see appendix WP 2 – A7).

Conclusions

There are several methods for preventing bacterial growth, but the most effective method is at the moment to use a bactericide. The bacterial growth is inhibited or decreases in rinse water with a concentration of 100 ppm of Triameen Y12D-30.

The problems with the incompatibility of the detergent can be solved either by choosing another biocide or by exchanging components in the detergent, or both. It is important that the biocide which is chosen is completely biodegradable within reasonable time. No traces should be left when the water reaches the environment or the next recipient.

In our opinion we believe a trade-off is needed. It might be an advantage to use a less environmental friendly detergent and consequently have a lower concentration of the biocide. There is no point in using extra environmentally friendly substances in the formulation, if it requires a biocide concentration of 100 ppm or higher for every tank after each wash cycle.

Future challenges

- Determination of the traces of biocides left in the clothes after a wash cycle.
- Reformulation of the detergent for compatibility with the biocide.
- Evaluation of lower concentrations of biocide in combination with other detergent formulations.
- Evaluation of other techniques as alternatives to the usage of biocides.

WP3 – Detergents

The problem

The challenge of the work package was to develop a liquid detergent formulation that was based on environmentally benign components and that gave good cleaning results at 30 °C. It was decided that bleaching agents, as well as optical brighteners, should not be included in the formulation. They are not part of the detergent action and may, if needed, be added in the final formulation. It was also decided that the initial screening work should be done with a formulation that gave maximum attention to the cleaning action by the surfactants. Enzymes and antiredeposition agents were therefore not part of the starting formulation. They were incorporated at a later stage but they were not optimized for the purpose. Dye transfer inhibitors and perfume were not used throughout the project.

Results

It was decided from the beginning that the formulation should as much as possible be based on nonionic surfactants. This is contrary to most commercial formulations of today, which have anionic surfactants as the major component and nonionics as a smaller constituent. (Anionic surfactants are surfactants that contain an anionic group, usually a sulphonate or a sulphate group, as polar head group. Nonionic surfactants have an uncharged polar head group, usually a polyoxyethylene chain.) There were two reasons why nonionics were preferred. Firstly, compared to anionics, their performance is much less affected by salts. With the special procedure of reusing water that is the core of the S´wash concept one can anticipate a higher than normal concentration of electrolytes in the washing step. Secondly, nonionics are often more environmentally benign than anionic surfactants.

A wide range of formulations were tested based on different combinations of medium chain alcohol ethoxylates, alkyl glucosides and amine oxides as surfactant system. The surfactants were supplied by AkzoNobel Surface Chemistry and were all commercial products with low and documented environmental impact.

Foaming experiments were performed at Chalmers using a modified Ross-Miles Foam Height Test (ASTM D1173) and also in Unilever's laboratory. Based on these tests it was decided to add a small amount of soap to the detergent formulation. Soap is a known foam control agent in detergent formulations. The soap was Prifac 5908 from Croda, which is based on hydrogenated palm kernel fatty acids. Soap is regarded as an environmentally benign component of a detergent formulation.

Screening of the liquid formulations was performed at Unilever's detergent laboratory in the Netherlands using a laboratory robot.

The effect of the formulations on a broad range of different stains, such as clay, black shoe polish, dirty motor oil, lipstick, red curry, blood, grass rubbed into the fabric, black tea and red wine was assessed. A representative test result is shown in appendix WP3 – A1, where five experimental formulations were tested on 23 different stains and compared with a high performing standard liquid formulation called Maradona. One should note that Maradona is a full formulation that contains enzymes, an antiredeposition agent and a dye transfer inhibitor. As can be seen, apart from one stain, lipstick, the test formulations performed reasonably well compared with Maradona's values.

Based on the results from Unilever's test, a formulation referred to as S´wash L3 was selected. The main surfactant component of this formulation was Ethylan 1005 [ii]. This nonionic surfactant is known to be excellent in terms of wetting and removal of fatty soil. It is readily biodegradable, its LC50[i] value on fish is in the range 10-100 mg/l and its EC50[iii] on daphnia magna and algae is also in the range 10-100 mg/l. Two other nonionic

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[i] LC50, Lethal Concentration 50, is the concentration of a chemical which kills 50% of a sample population.
[ii] Ethylane 1005 is a narrow range C10 alcohol ethoxylate, penta(ethylene glycol)monopropylheptyl ether, with a cloud point of 47-53 °C and a HLB of 11.6.
[iii] EC50, Effective Concentration 50, is the concentration of a chemical that gives half-maximal response.

surfactants were present in smaller amounts in the S´wash L3 formulation, AG 6210 and Aromox MCD-W. AG 6210 is a sugar based surfactant, a mixture of decyl and octyl glucoside. It is readily biodegradable and its LC50 and EC50 values are in the same range as for Ethylan 1005. Aromox MCD-W is an amine oxide surfactant, fractionated coconut (mainly dodecyl) dimethylamine oxide. It is readily biodegradable. Its LC50 on fish is in the range 1-10 mg/l, its EC50 on daphnia magna is also in that range and its EC50 on algae is in the 0.1-1 mg/l range. None of the three nonionic surfactants is classified as bioaccumulating.

Tests in experimental washing machines were subsequently performed at Unilever and at Swerea-IVF. Besides the three nonionic surfactants and soap, the formulation contained monoetanolamine for pH control and monopropylene glycol as hydrotrope. Two enzymes, one protease and one amylase (Savinase 24GTT and Stainzyme 12GT, respectively, both from Novozyme) were also added into the formulation. The water hardness was kept at 25 FH[iii] and the pH of the washing liquid was in the range 7.0-7.5. At a later stage carboxymethyl cellulose, CMC, was added as antiredeposition agent. Swerea-IVF's test results are given in appendix WP3 – A2. The complete formulation used (S´wash L3), still without dye transfer agent, optical brightener, bleach and perfume, is given in appendix WP3 – A1.

The machine tests indicated that the soil removal was comparable to commercially available detergent formulations after initial tests. After several washing cycles, greying could be seen on white fabric, however. This could possibly be due to poor performance of the antiredeposition agent used. It could also be due to the lack of a dye transfer inhibitor in the formulation.

A special problem associated with the S´wash concept is that of bacterial growth in the tanks in which rinse water is stored. One approach to overcome this problem is to add a bactericidal cationic surfactant. A cationic biocide from AkzoNobel was tested at a concentration of 100 ppm, which was regarded as sufficient to control bacterial growth in the water containers. However, addition of this compound gave rise to precipitation in the liquid formulation. Most likely, the positively charged amphiphile formed an insoluble complex with the negatively charged alkyl carboxylate of the soap.

[iii] FH, French Hardness. The unit is used for specifying the salt concentration in water.

Future challenges

The main remaining items are:

1. To avoid greying of white fabric after repeated washing cycles. Different antiredeposition agents, as well as dye transfer inhibitors, should be tested for the purpose.

2. To reformulate the detergent so that a cationic biocide can be incorporated. One way to do this is to replace the soap by a foam control agent that is compatible with the biocide.

WP4 – Sensors

The focus of WP4 was to evaluate sensors that could be of interest for this application i.e. to on-line analyse bacteria, biofilm, colour, detergent concentration, free micelle formation and different kind of soils.

The problem

Re-use of rinsing water stored in tanks between washes is aimed at in the S´wash solution. Rinsing water contains textile fibre, nutrients from dirt and cells and colour pigments from previous washed textiles. To secure safe use of the stored rinse water there are two critical parameters that needs to be controlled and they are:

- monitor the growth of bacteria in order to determine when actions are to be taken
- monitor the quality of the recycled water with regards to colour pigment concentrations

The challenge is to have maintenance free sensors that can perform in a system that, at present, is far from standardized. The system can be a combination of different soils, water hardness's, low pH, high temperature, biocides, detergents, softeners, bacteria and biofilm. Other physical factors that can influence the analysis are variation in temperature and humidity.

Results

First a theoretical screening of possible sensors techniques suitable for analysing the properties above was performed by simply considering which sensing techniques would allow measurements of the parameters singled out above and with little concern about their implementation environment. Thereafter we have chosen among the theoretically considered techniques the ones we thought would be most suitable with respect to the application environment and the associated constraints, for example price, robustness, etc. Table 3 presents identified sensors for measuring the different parameters.

Table 3. Analysis techniques summary

Technique	Bacteria	Colour	Detergent
Magneto Elastic Resonance (MER) for Biofilm	X		
IR(Infrared)-gas sample (CO2-bioactivity)	X		
NADH fluoresces	X		
UV/VIS (Visible Spectrum)		X	X
Diodes in colour wavelength RGB		X	
Digital Camera		X	
Acoustic			X
IR/NIR (Near IR)			X
Conductivity and impedance			X

(green)	Good analysis performance and could be implemented in a washing machine
(yellow)	Good analysis performance, needs more development before implementation
(orange)	Poor analysis performance or not suitable in a washing machine
(red)	Does not solve the analysis task

The most interesting analysis techniques were then used for initial trials of analytical performance for the different properties. Some of the instruments were reference instruments with full spectral and analytical range. These were used to determine specifications for the possible future construction of dedicated sensing equipment. For example we use commercial laboratory spectrophotometers and VIS/NIR instruments to narrow down the wavelength range(s) to determine the range and number of filters that one would need if decided to construct a simple dedicated system. All analysis techniques marked as green or yellow in Table 3 were chosen for further evaluation.

Bacteria measurements

The water stored in the tanks after rinsing contains textile fibres and nutrition from stains (i.e. dirt, blood, cells, grass and bacteria). These are very good initial condition to induce bacteria growth. Bacteria growth can be measured through many different techniques. Here we have found it suitable for this application to measure CO_2 in air as an indirect measure of biologic activity (respiration). Another technique that could be suitable was to measure the NADH (Nicotinamide adenine dinucleotide) fluorescence. The bacterial colony grows actively and at a high rate only when the colony is disturbed from equilibrium by new nutrition, it is stirred or by other changes in its surrounding. The methods used by us here measure not the bacterial concentration per sé. They measure the bacterial activity and assume it to be proportional to the bacterial concentration. Qualitatively this is correct, at least during bacterial growth stage. However quantitatively the statement does not hold; - small but vigorous bacterial colony would produce as much CO_2 as much larger colony of low activity. However, given that our bacterial populations were very high (millions of CFUs/mL see appendix WP2 – A3) the simple proportionality assumption is not too bad.

As we have shown in the measurements with both CO_2 and NADH (see results below and appendix WP4 - A2) there is not a straight forward correspondence between the CFU/mL established in a laboratory culture tests and our measurements. For example, when the rinsing water system was left alone its bacterial population reaches equilibrium after a few days and the bacterial activity decreased to more or less nothing. Measurements at that period would signal bacteria-free water! However the strength of our techniques is that they can be adapted for intermittent or continuous on-line measurements made so frequently that the chances to miss the increased activity would be negligible.

CO_2 analysers are well-known and inexpensive. They are commonly used as sensors to monitor e.g. air quality. Two bottles were prepared containing rinse water from normal household laundry and a small amount of sugar as bacterial culture media. The biocide Triameen Y12D-30 was dosed in one of the bottles. A Non-dispersive infrared absorption CO_2 sensor from Gas Sensing Solutions was placed in the air above each bottle and the concentration was measured during five days. In Figure 3 it can be seen for the bottle without added biocide that the concentration rises after approximately 1-1.5 days, peaks after 3-4 days and then starts to decrease by the end of the five days. For the bottle with added biocide there is no increase of concentration during the five days. The noise seen as peaks on shorter time intervals than the five days in Figure 3 are due to daily variations in CO_2 coming from surrounding air (co-workers in the lab).

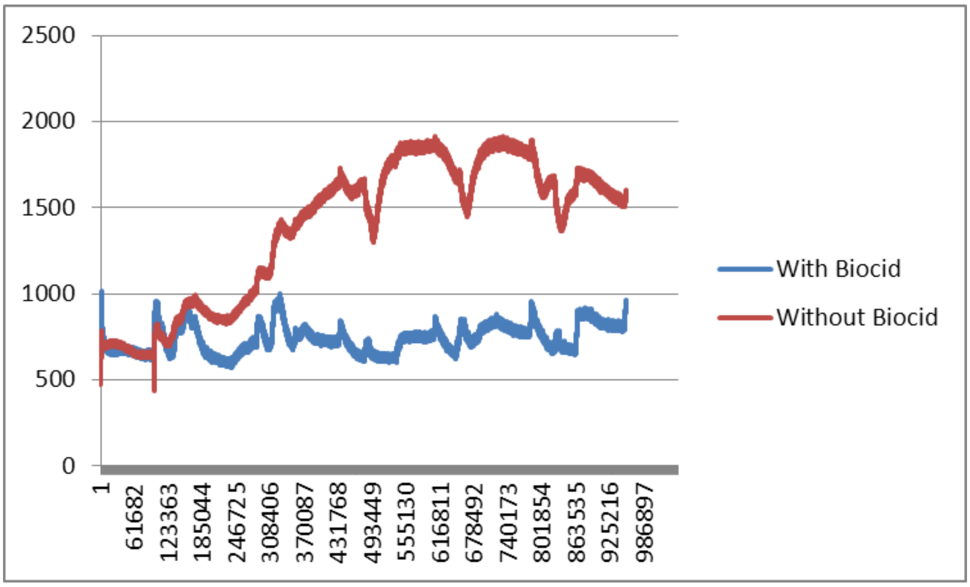

Figure 3. CO_2 concentration (ppm) in air during five days for two samples of rinsing water where one sample had added biocide. X-scale is number of measurement with approximately two per second.

The conclusion is that CO_2 can be used as an indicator for bacteria growth, at least as a qualitative response for when water in tanks needs to be flushed out.

NADH fluorescence takes place over a wide range of wavelength intervals, much larger than what one usually finds for molecular fluorophores, see appendix WP4 – A2 for more details. It has been shown that different microbial families produce slightly different characteristic NADH fluorescence. Due to a large variety of different microbial families in the rinse water the results of the NADH fluorescence was spectrally broad and featureless.

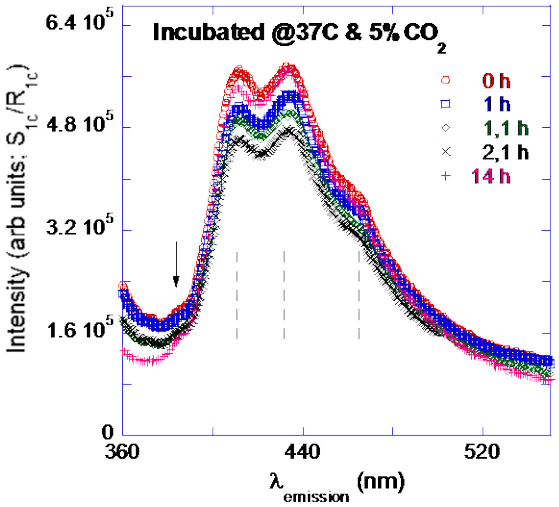

Figure 4. The fluorescent emission from the as-received rinsed water samples after different incubation times. Note that sample returns to its native state (red curve) after overnight incubation (pink curve).

It seems to be possible to control bacterial activity using NADH fluorescence. Moreover it is possible to construct a simple and cheap sensor system that would monitor such activity on-line. Such system requires also measurement of turbidity. The latter can be easily achieved using the same set-up.

The results suggest that both peaks and a small shoulder at approximately 480 nm are all due to bacterial activity. Unfortunately, the samples mixed with the biocide also show maximum around 420nm. Therefore it is no trivial matter to unanimously establish whether there remain the type of bacteria still living that produce this particular emission or not. This can be resolved however by compensating for different turbidity of the sample. Measure the decrease of the intensity of the incoming light after it has passed through the cuvette, and not only before it enters the cuvette. Later on in the analysis one can use the decrease to (artificially, via software) normalize the measured fluorescent intensity to the different turbidity by taking one of the fluorescent spectra and the associated sample turbidity as an arbitrary reference.

Another interesting technique that could be used for monitoring biofilm growth is MER (Magneto Elastic Resonance). It has been used to follow the biofilm growth and showed that it is possible to mimic surfaces of the water tanks and monitor biofilm growth at any time.

MER is a technique that uses a magnetically biased foil made of magneto elastic material that oscillates when exposed to sign reversed AC-magnetic field. The method allows measurement of two parameters: the resonant frequency shift and the so called Quality factor (inverse of the energy dissipation that takes place when the foil oscillates). The resonance frequency of these longitudinal oscillations depends on the mass load on the foil – the frequency decreases with increasing mass load. The quality factors related to the viscos-elastic properties of the over layer. The softer the film the lower is the measured Q-value (the higher is the dissipation). In other words, one needs more energy to drive the foil.

The biofilm increases the weight of the foil which lowers the resonance frequency of the foil. The deposited mass is directly proportional to the frequency. The results from measuring rinse water were a reproducible mass uptake as shown by the continuous frequency decrease, and simultaneous dissipation increase, of the growing biofilm (see appendix WP4 – A3). MER could be a possible solution to measure biofilm growth wirelessly using magneto elastic resonance technique. The technique is cheap (each probe costs <0,01€) but probes will need to be exchanged after some time due to prohibitively thick biofilms that would form over years.

Colour measurements

To avoid staining between washes from coloured water the water was measured by UV/VIS, diodes and a simple webcam. The UV/VIS measurement indicated which wavelengths were of interest for this application and gave input for the choice of four diodes. The diodes and webcam were used in a test where water from colour bleeding textiles was collected and measured before it was used for staining strips of reference textiles, see appendix WP1 – A4 for more information about the test. Using partial least squares (PLS[3,4]), a prediction model was calibrated with data on measured response of colour on rinse water and the amount of staining on the reference strips. The model uses information from all four diodes to predict the staining on the strips. The results indicates that the three worst colouring samples (sample 1D, 2E and 2D in Figure 5) can be analysed and give a control signal to be flushed out in the drains. The sensitivity of the analysis must be evaluated further and in combination with a final formulation of detergent where there are anti-dye and anti-repodisition agents present. Similar results were achieved with the webcam, see appendix WP4 – A1.

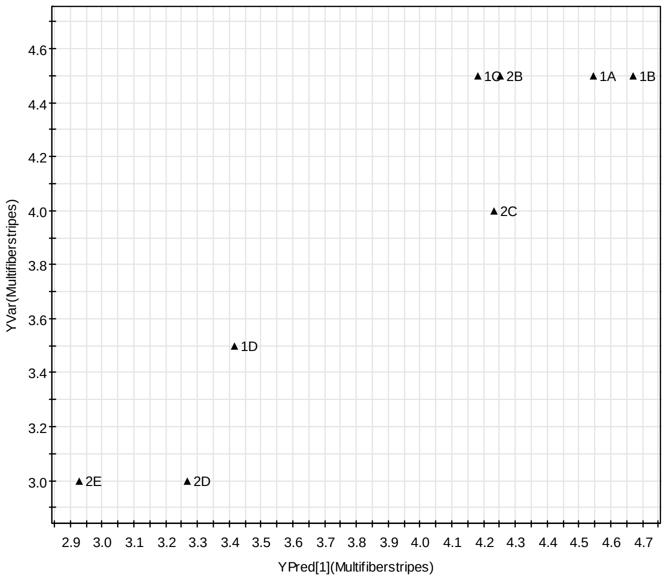

Figure 5. Predicted versus observed values (in greying scale 1 to 5, where 5 is no visible change from reference) for staining on multi fibre strips from PLS model based on diode measurements.

Detergent measurements

It was found that it is possible to follow detergent dosing by a simple DC-conductivity measurement. By measuring the impedance one could also determine the critical micelle concentration, CMC, for a given detergent. Impedance measurement can therefore be used to monitor dose for different water hardness's since CMC depends on (among other things) how hard water is. Both methods are simple in use and robust, and can be made cheap using available electronics, see appendix WP4 – A4 for a detailed report. The tests have only been performed in solution without dirt or other disturbance factors you could have in a washing machine, this was due to that we had to focus on colour and bacteria since these were showstoppers for the project.

Future challenges

The sensors have not been tested for prolonged use which would be necessary before thinking of implementing them in the production of washing machines.

WP5 - Environmental analysis

The problem

A possible risk when developing new technology is that a reduced environmental impact in one environmental aspect, or in one part of the life cycle of the product, causes negative environmental impact elsewhere. A useful tool in avoiding this type of sub-optimization is an environmental life cycle assessment (LCA).

Results

Here, a consequential life cycle assessment (LCA) has been performed on the prototype S'wash washing machine and detergent to quantify its environmental impact compared to a typical washing machine used in Sweden (40 °C and 60 °C) and Spain (no heating of water and 60 °C).

The study has largely been performed in accordance with the international standard ISO 14044 (ISO, 2006), but has only been reviewed internally in the project and not by a third party.

The results of this study indicate that the efficiency goals for water and electricity use during washing have been fulfilled; see Table 4. It has not been possible to fully assess the difference in environmental impact of the detergent, and it has been beyond the scope of this study to ensure that the same washing performance was achieved in the project.

Table 4. Environmental goal fulfilment of the S'wash prototype used in this study.

	S'wash system	**Typical domestic washing system (60 °C)**	**Goal fulfilled?**
Freshwater use	3.4 litres/kg load	16 litres/kg load	**Yes (-79%)**
Detergent	*Data quality too low to assess. The amount of detergent should, however, be reduced due to automatic dispensing*		
Electricity use	0.083 kWh/kg load	0.35 kWh/kg load	**Yes (-76%)**

Based on the results of the life cycle assessment (LCA), the study concluded that:

- In Sweden, an additional wash using the S'wash system causes a much lower environmental impact than a 60 °C typical wash, and somewhat lower environmental impact than a 40 °C typical wash for the impact categories included in this study[iv]. This is mainly because a S'wash wash requires a smaller increase in the marginal electricity production.
- In Spain, an additional wash using the S'wash system causes about the same environmental impact as a 15 °C typical wash, and a much lower environmental impact than a 60 °C typical wash for the impact categories included in this study.
- Two water use impact categories were used as the area is quite new to LCA: water stress index and ecological scarcity. Both methods indicate that water use in the washing itself is the most important. There are, however, limitations in the life cycle inventory data, such as the use of average OECD characterisation factors had to be used for all water use data in the background system

[iv] The included impacts were mainly climate change, acidification, eutrophication, photochemical oxidant formation, primary energy demand and water use.

- The data quality of toxic impacts is too low to be able to draw any conclusions regarding the relative impact of the washing systems from a life cycle perspective. A risk analysis was attempted on the detergent ingredients remaining in the water after washing. This screening showed that it is possible that the detergent ingredients in both the typical detergent and the S'wash detergent may cause acute toxic impact on aquatic organisms if the water is discharged into nature with only primary wastewater treatment.

Based on these conclusions, the following recommendations were given for the continued environmental work for the S'wash system and for future studies:

- Reduce the uncertainties in material composition, detergent, and toxic impacts. This can be achieved when the S'wash system is closer to the market, and is thus a more comparable alternative.
- Differences in wear and tear, as well as in cleaning quality should be investigated further.
- The drying part of the washing process should not be left out for a full assessment of the environmental impact from domestic laundry, as a tumble dryer may require as much electricity as the washing itself.

Main project results

The main project result is that it is found possible to lower the water usage to as much as 79 percent without losing in cleaning performance. What is affected is rinse performance after multiple washes, staining after wash with colour bleeding textiles and bacteria growth. These are issues that could be solved by further development of detergent formulations, implementation of sensors and use of proper biocides. When using reference detergent IEC-A there are no greying after multiple rinses so using a combination of antiredeposition agents, dye transfer inhibitors and perhaps bleach in the detergent formulation would increase rinse performance. A set of diodes could monitor coloured water to flush out too heavily pigmented water and a NADH or CO2 sensor could tell if we had bacteria growth in the washing machine.

It was found difficult to lower the energy consumption without losing out too much in cleaning performance, alternative techniques or detergent formulations must be developed to solve this challenge.

It was possible to develop a very environmentally benign detergent that had similar performance as commercial detergent formulations. In combination with automatic dosage this would lead to a very good environmental footprint. LCA for toxicity is however in its cradle and therefore it is difficult to give a quantitative measure of the environmental footprint for this conclusion.

Dissemination

S'wash has received great interest in a number of forums. It is a project that most people can relate to since almost everyone uses a washing machine on a regular basis. The budget for dissemination and exploitation was limited but S'wash has been published in NyTeknik and Bofast. The project has been presented at the SEPAWA stake holder meeting, at the 45th International Detergency Conference in Dusseldorf and also at the stake holder meeting for the Nordic Eco-labelling.

Conclusions

From discussions with external parties it was found that a major future challenges is to take an overall view of the total system performance regarding the region and its prerequisites, cleaning performance, environmental impact, water resources and wear of clothes. This conclusion comes from discussions with people representing different parts of the value chain for washing machines (Svanen, Bra Miljöval, Energimyndigheten, Gryaab and producers of machines, detergent and clothing companies). An effective detergent could be more environmental friendly in a system than as a standalone product since it lowers the need of high temperature to reach the same cleaning performance. This will be a challenge for correct labelling and settings of standards for products since they need to be included in an appropriate system to perform at its best.

Consumer behaviour is the second major challenge for the future. Will they approve the concept of the S'wash washing system? You have to put your trust in the machine to perform the correct dosage as well as take decisions regarding limits of bacteria growth and colour in water to not affect the cleaning performance. Another big issue for households approving a S'wash washing machine is that they will need to use a biocide to solve the bacteria growth problem. For laundry houses, where the washing machine is used more often, bacteria growth will not be of equal concern. The water can be flushed out after the last wash every day and still the overall water consumption would be a lot less.

Main Future challenges foreseen by the project

There is a big challenge to make the public and also labelling organisations acknowledge that to find the best solution we cannot look at all the parts of the washing system separately. We need to put all the components and pre-requisites together to make a knowledge based decision. Questions one need to ask is:

- What is the major environmental benefit we could get from a system within our system boundaries? Is the environmental challenge heaviest on water, energy or chemical load?

- What is the acceptance for new technical solutions from the users?

- Overall, changes needs to be performed on several areas for the system: Changing washing attitudes by maximizing textile-load.
- New environmentally friendly detergents.
- Systems preventing overdosing.
- Systems dosing water by textile weight, water hardness, etc.

If the focus is on more intelligent washing machines and consumer acceptance it will lead to a dramatically decrease in water consumption.

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