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Influence of Water Circulation in Household Washing Machines on Cleaning Performance

Washing machines use different technologies to enhance their washing performance. Despite different names, some of these technologies use additional circulation pumps. These pumps allow spraying of suds into the inner drum and circulation of suds in the gap between the inner and the outer drum. A washing machine without circulation pump was used as a reference. Experiments were carried out similar to typical household conditions using a 40 °C program for cotton. A set of 20 stains was used to evaluate the primary washing effect for different stain groups and of individual stains. The results showed that generally, the circulation pumps did not change the performance. However, for two stains significant advantages could be found only in the case of a system with two circulation pumps for two single stains, CS32 sebum and CS06 salad dressing. It is concluded that the differences between machines from different manufacturers are mainly influenced by variations of the parameters according to Sinner's Circle.

Key words: Textile washing, washing performance, washing technology, circulation

Einfluss von Umwälzpumpen auf die Waschleistung von Haushaltswaschmaschinen. Waschmaschinen nutzen verschiedene Technologien, um die Waschwirkung zu erhöhen. Ein Teil dieser Technologien beruht trotz sehr unterschiedlicher Bezeichnungen darauf, dass zusätzliche Umwälzpumpen eingesetzt werden. Durch die Pumpen kann die Waschlauge in der Trommel direkt auf die Wäsche aufgesprüht werden bzw. im Spalt zwischen innerer Trommel und äußerem Laugenbehälter umgewälzt werden. Als Referenz wurde eine klassische Waschmaschine ohne Umwälzpumpe getestet. Ein Set von 20 Anschmutzungen wurde eingesetzt, um die Fleckengruppen und Einzelflecken miteinander zu vergleichen. Die Versuche in 40 °C-Programmen für Baumwolle orientierten sich an haushaltsnahen Bedingungen. Die Ergebnisse zeigen nur geringe Unterschiede, die auf die Umwälzpumpen zurückgeführt werden können. Nur für ein Gerät mit zwei Umwälzpumpen konnten signifikante Unterschiede bei zwei Einzelflecken, CS32 sebum und CS06 salad dressing, zum Referenzgerät gefunden werden. Daher wird davon ausgegangen, dass die Hauptunterschiede in der Waschleistung von Geräten verschiedener Hersteller vor allem durch geringfügige Unterschiede der Parameter gemäß dem Sinner'schen Kreis verursacht werden.

Stichwörter: Waschen, Waschwirkung, Waschtechnologie, Umflutung

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1 Introduction

The principle of household washing machines has not changed for more than 50 years. The detergent is normally flushed into the machine by tap water to form washing suds. During the main wash phase, the textiles and the suds come into contact by the rotation of the inner drum. The removed soil and remaining detergent are flushed out by using tap water for rinsing in several steps. In the main wash phase, the temperature and detergent concentration are much higher than during rinsing. Therefore, the conditions in the main wash phase such as duration, temperature, detergent (type and concentration) and mechanical forces have the highest impact on washing performance. They are usually referred to as Sinner's Circle parameters. Lee [1] showed the effects of mechanical abrasion, flexing of textiles and hydrodynamic flow on washing performance. In this study, the experiments were conducted on a small laboratory scale. In the case of flexing and hydrodynamic flow, soiled textile strips were moved back and forth through a detergent solution. In the hydrodynamic mode, the textile was tightly held by two grips. In the flexing mode, the textile between the grips was longer, allowing bending and flexing during the oscillating movements. It was shown that the removal of particulate and composite soil was dependent on the mechanical action type. Bending, for example, was a combination of flow and mechanical movement.

There are many attempts to establish new washing technologies worldwide. The approaches can be divided into solvent and physical systems. In the first system, the idea is to replace water as the solvent. A professional application is the dry cleaning process that uses perchloroethylene (PER) or hydrocarbons as solvents. The physical systems can be further divided into enhancement systems which do not change the basic washing principle, but promise some kind of a superior washing performance. Other examples are the use of ultrasonic for pre-treatment of stains or electrolysis to improve hygiene. But none of these systems have become a standard for household washing. An overview can be found in Schambil et al. [2]. A more recent physical approach to change the basic washing system is the use of plastic beads. Made public in 2007, this system is still waiting for an independent evaluation [3].

Nevertheless, the classical horizontal axis machines are dominant in the European market and are expected to gain market shares in developing countries as well. As the amount of water was drastically reduced from about 205 L in 1970 to 44 L in 2015 per washing cycle [4], the water level dropped to the lower end of the inner drum. Therefore, technologies were developed to enhance the contact between the suds and the textiles [5].

The first is a passive attachment to the inner rotating drum that rains water on the laundry as the drum rotates,

see Fig. 1. For this purpose, baffles are attached to the inner side of the inner drum which fill with water at the bottom and rain the suds at a higher position onto the laundry. We will classify this kind of system as Standard in the text.

We will compare this Standard-System with systems that have baffles and circulation pumps. These pumps circulate water inside the outer drum or between the outer and the inner drum, see Fig. 2. As the water flow can be designed in different ways, we will compare systems that make different uses of the circulation system. The circulation pump should not be mistaken for another type of pump that is only used to flush out the suds after the washing and rinsing process, and which has no influence on the washing performance. Systems with a circulation pump normally have at least 2 in-built pumps. In most cases, the presence of a circulation pump is accompanied by advertising claims of a higher washing performance or a change in the washing regime.

In the Spray-System, circulation takes place between the outer and the inner drum. The suds are sprayed directly into the laundry, in most cases visibly near the glass door. The main effect expected is a more intense mixing of the suds and the textiles, leading to higher availability of detergent components. This could result in a faster detergent action and better removal of the loosened stains. As a side effect, this could also enhance the mixing of the detergent and the water. In some cases, it could also lead to the deposition of detergent powder on the textiles in the starting phase.

In the Premix-System, the water is usually circulated in the outer drum to dissolve the detergent before mixing the suds with the textiles. Especially, powder detergents dissolve more slowly than liquid detergents with low viscosity. The associated claim is that the detergent acts faster.

The Airmix-System is similar to the Premix-System as water is circulated in the outer drum. But every time this kind of Premix-System is working, air is additionally sucked into the water flow by the Venturi effect. Therefore, we will refer to this system as Premix & Airmix-System in the text.

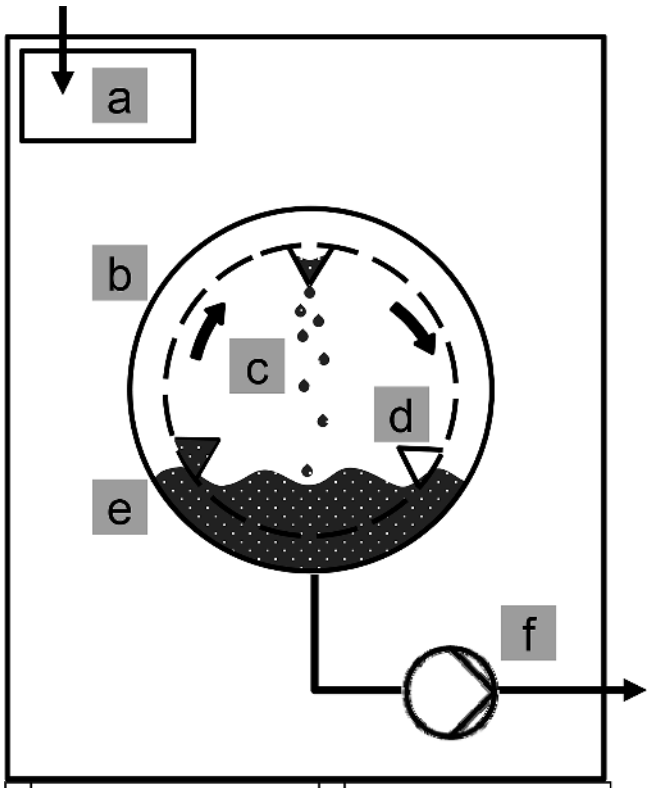
The first question is whether the washing performance of machines with circulation pumps is generally higher. This could be expected if the distribution of the detergent is more uniform or established faster. In order to get a high effect, a powder detergent will be used.

The use of the Spray-System changes the ratio between the mechanical forces applied by the movement of the textiles due to drum rotation and the hydrodynamic action owing to water flow through the textiles. This leads to the second question of whether the washing regime is changed by the use of a circulation pump in such a way that would make it necessary to adjust the detergent composition. In order to find out if there is such an effect, we will have to compare individual stains. This is because in extreme cases, some stains could be removed better and some worse while maintaining similar levels of the overall washing performance.

2 Material and Methods

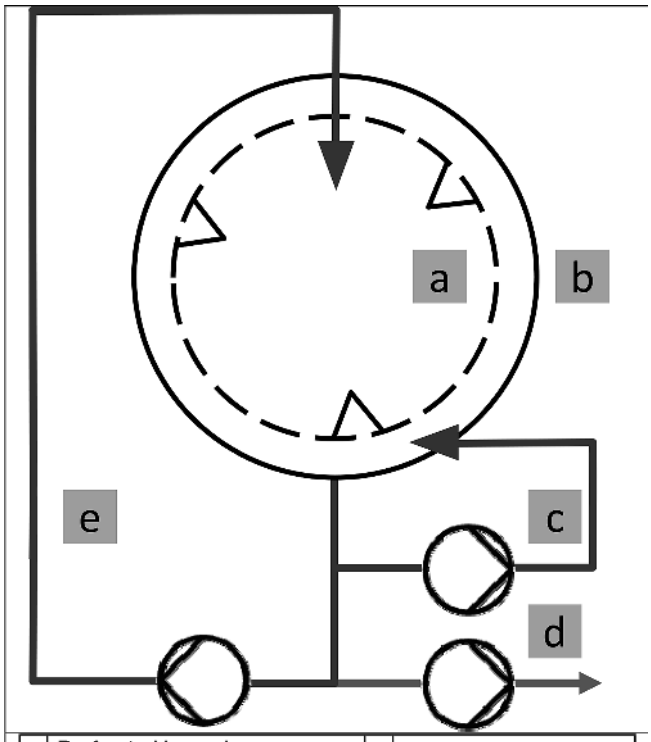
2.1 Washing machine types

For the purpose of comparison, three types of washing machines that differed in how they used circulated water, see Table 1, were chosen. Miele Softronic 1935 was used as a



a	detergent mixing drawer	d	baffle attached to c
b	outer fixed drum	e	water at the lower end
c	perforated and rotating inner drum	f	suds pump

Figure 1 Standard-System with passive baffles



a	Perforated inner drum with baffles	d	Suds pump for draining
b	Outer drum	e	Circulation pump for spraying suds into (a)
c	Circulation pump for circulation in the gap between (a) and (b)		

Figure 2 Illustration of different waterways

standard for comparison as it has no additional circulation pumps and circulates water according to Fig. 1 only by using baffles. A Candy Evo 1494 LW-84 machine was used for the Spray-System. It sprayed the suds as a visible water jet into the inner drum. This is thought to enhance performance by better contact between the suds and the textile. The Spray & Premix-System was represented by AEG Lavamat L89495FL, which also sprayed suds into the drum with a less powerful jet. But additionally, the suds were circulated in the gap between the inner and the outer drum. In illustrations for consumer communication, sometimes a separate compartment is shown where the mixing takes place. In reality, the gap between the inner and the outer drum is used for premixing and there is no separate in-built compartment. This premixing boosts the dissolution of detergent in the suds before coming into contact with the textiles. The third washing machine, Samsung WF0804Y8E, used only a circulation system, but in a modified way. It was able to suck in additional air by the Venturi effect. This would affect the circulation flow in the gap between the inner and the outer drum. This system was originally called "bubble" or "foam" wash by the manufacturer. In order to have a uniform classification scheme, however, "Premix & Airmix" will be used instead. Since the water flow in this system was only injected between the inner and the outer drum, in contrast to other systems that included some kind of spray action, the consumer was unable to visually perceive if the system was working or not. The different waterways in the machines, both with and without the circulation pumps, are illustrated in Fig. 2.

2.2 Soils and Detergent

A set of 20 different stains was used, which is typical for the evaluation of detergent performance. Individual stains were from the Center for Testmaterials B.V. (CFT) and wfk Testgewebe GmbH. Six stains were sensitive to bleach, 5 to enzymes and 9 to mechanical action. The stains that were sensitive to mechanical action were usually also sensitive to the surfactant systems. Therefore, it is usually difficult to distinguish between mechanical and surfactant action. This is the reason why the detergent concentration was held constant in all experiments. The textile substrate was mainly cotton; only two stains were used on a mixture of polyester and cotton (see Table 2).

According to DIN EN 60456 specifications for the evaluation of washing performance, there are only 5 stains: sebum, mineral oil mixed with pigments, blood, chocolate and red wine [6]. In order to get a better overview, a set of 20 stains was used, with the stains being different in details, but comparable in soil types.

In the household, the load usually contains high amounts of soil types like i. e. body soil and dust which have an influence on detergency but are barely visible. In order to reflect this, usually soil mixtures are added to the clean load in laboratory experiments that resemble natural soil. Sheets of *SBL 2004* from wfk Testgewebe GmbH were used as soil ballast. One piece contained 8 g of soil. A typical German high-grade heavy-duty powder detergent with bleach was used as detergent.

2.3 Washing Conditions and Measurements

The chosen load and textiles were similar to typical household conditions, consisting of 70% cotton and 30% polyester. According to DIN EN 60456 tests to evaluate washing performance are done at 50% and 100% of the recommended maximum load. Since consumers do not weight the load and it is very difficult for consumers to get in the maximum load, experiments were carried out at 75%.

The textiles and stains were put into the drum similar to the DIN EN 60456 procedures. In order to get a comparable detergency, the concentration of detergent and additional soil in the main wash phase was kept constant. Concentrations in the main wash phase were 3 g/L detergent and 2 g/L soil from *SBL 2004*. If the amount of water in the main wash cycle was lower than in the preliminary experiments, the water amount was manually adjusted by filling water in the detergent mixing drawer. Thus the concentration of detergent could be held within narrow limits at 3 g/L in all machines. The washing program was chosen so as to achieve a similar washing time and high mechanical action.

Washing programs at 40 °C chosen were recommended for a high washing performance and were suited for laundry made of cotton, the program and options can be found in Table 3. In DIN 60456, cotton programs at 60 °C and 40 °C were used to evaluate the washing performance. A mean washing temperature of 40.1 °C was reported in a survey commissioned by the International Association for Soaps, Detergents and Maintenance Products (A.I.S.E.); about 5000 participants were surveyed in 2011 [7]. According to Wagner, the most frequently used programs in Germany ran at 40 °C [8].

Each experiment had 4 repetitions with 2 sets of stains, giving 8 measurements of stain removal. To measure performance, the luminance of the textiles was measured with a reflection spectrophotometer, Datacolor 600 from Datacolor Inc. The value 0 corresponded to black and 100 to white; values were reported in graphs as Y, which was defined as relative luminance according to CIE 15.2. In order to reduce variations for the calculation of the average values of the 20 stains, the minimal and maximal values were omitted. For comparing the individual stains, all 8 values were used. Since the program structures of the machines from different manufacturers were not identical, the actual washing conditions would be shown first in the results section.

3 Results

The program structures implemented by the machines' manufacturers were not changed in this test. The programs were chosen so as to get comparable program times and temperatures. The difficulty was to find a matching pair of

	System	Number of pumps	Sketch of waterway in Fig. 2
Miele Softronic W1935	Standard	1	d
Candy Evo 1494 LW-84	Spray	2	d, e
AEG Lavamat L89495FL	Spray and Prexmix	3	c, d, e
Samsung WF0804Y8E	Premix and Airmix	2	c, d

Table 1 Overview of machines used as examples for the different circulation systems

programs at 40 °C and suitable program options. This was possible for all systems except the Premix & Airmix-System. The mean maximum temperature was in the range of 34 (±2) °C, and the program duration in the main wash phase was 103 (±9) min, see Table 3. Since the concentrations of detergent and soil could be adjusted manually, those values were within a much narrower range of 3.05 (±0.05) g/L and 2.05 (±0.15) g/L.

The conditions in the Premix & Airmix-System were similar to the others, except for the program duration. But as we wanted to use the option of switching on and off the Airmix system, we were not able to identify a program with a comparable duration to the other machines. In a second problem, it was observed that the program duration in the off mode was 10 min longer than in the on mode. Therefore, the main wash duration was much shorter compared to the other systems, and differed by 10 min between 30 and 40 min. Therefore, this system is discussed separately from the other machines.

Type	Description	Substrate	Sensitive to		
			Bleach	Enzyme	Mechanics
CFT BC2	Coffee	CO	×		
CFT BC3	Tea for low temperatures	CO	×		
CFT CS08	Grass	CO	×		
CFT CS103	Red wine, fresh	CO	×		
CFT CS12	Black currant	CO	×		
CFT CS15	Blueberry juice	CO	×		
CFT CS37	Full egg/pigment	CO		×	
CFT CS44	Chocolate drink	CO		×	
CFT CS26	Corn starch, colored	CO		×	
CFT CS28	Rice starch, colored	CO		×	
CFT CS06	Salad dressing/natural black	CO		×	
CFT C01	soot/mineral oil	CO			×
CFT C02	Olive oil/soot	CO			×
CFT C09	Pigment/oil	CO			×
CFT CS32	Sebum/soot	CO			×
WFK 20D	Pigment/sebum	PES/CO			×
CFT CS05S	Mayonnaise/carbon black	CO			×
CFT CS17	Make up	CO			×
CFT CS216	Lipstick red	CO			×
CFT PCS16	Lipstick, pink	PES/CO			×

Table 2 Stain set used for testing the performance of washing. The stains are divided into three groups, which are predominantly sensitive to the particular properties of the detergent or washing system. The substrates are cotton (CO) and polyester (PES)

	Standard	Spray	Premix & Spray	Premix & Airmix	Premix & Airmix
Load	5.25 kg	6.74 kg	6.75 kg	5.95 kg	5.95 kg
Program at 40 °C	Cotton	Intensive	Boiled/Coloured	Cotton	Cotton
Program option	–	–	–	EcoBubble on	EcoBubble off
Detergent	74 g	78 g	84 g	68 g	68 g
Soil SBL	48 g	56 g	56 g	44 g	44 g
Water total	98 L	116 L	97 L	89 L	89 L
Water main wash	24 L	26 L	28 L	22 L	22 L
Temperature max.	32 °C	36 °C	35.5 °C	37 °C	37 °C
Duration program	153 min	159 min	164 min	110 min	123 min
Duration main wash phase	97 min	100 min	112 min	55 min	65 min

Table 3 Comparison of the washing conditions. Load was 75 % from the recommended max value, detergent concentration in the main wash was 3 g/L and soil ballast SBL 2004 ratio to water was 2 g/L

3.1 Washing performance

The washing performance of the Standard-, the Spray- and the Spray & Premix Systems showed significant differences as the confidence intervals did not overlap. The mean luminance was in the range of 63.2 (±1.3), see Fig. 3a. The broader standard deviation of 0.8 luminance in the case of the Spray System compared to 0.2 luminance for the Standard-System was probably due to the relatively high amount of foam that was produced by a spinning cycle at the beginning of the washing program.

The differences shown in Fig. 3 are small when compared to the differences between a powder detergent with bleach and a liquid detergent without bleach. At comparable conditions, the detergent with bleach usually had 7% higher luminance; even when the stains that were predominantly sensitive to bleach were omitted, the difference was still 4.5%. The Premix & Airmix-System had the lowest performance as the washing time was much shorter, see Fig. 3.

Surprisingly, the circulation pump did not lead to higher performance in this test. As data from independent studies were unavailable, only consumer test data could be used as reference. Data from the German consumer test organisation Stiftung Warentest for the period 2014 to 2015 showed that even machines without circulation systems could achieve the best overall marks or best marks for cleaning performance [9, 10]. Only 50% of the 6 overall best rated machines had circulation systems, and the best rated machine of 2015 had a circulation pump, but it did not have so in 2014. Since these systems are well known for decades, this means that the presence of circulation pumps does not automatically lead to better results. But in the case of consumer tests, the conditions usually differ much more when compared to the conditions used in these experiments, i. e. program duration, and they are therefore less suited to compare technical features.

Therefore, the Premix & Airmix-System was additionally compared with the same program in the off mode, which was prolonged by 10 min. The Premix & Airmix-System with a shorter main wash phase as compared to the Standard-System showed no difference in performance between the on and the off modes. This was also surprising because the cycle time was 10 min longer in the off mode. The high standard deviation of 0.8 luminance for the Premix & Airmix-System in the off mode, see Fig. 3b, was not caused by a high foam level, as the foam level was low. The reason for the higher deviation could be due to the switching off of the circulation pump, and in this case, the detergent was probably distributed less evenly.

On the other hand, even if the mean performance was on the same level, it could have been the case that the circulation system changed the soil removal of the different stain groups, and so the stain groups were analysed in detail. The stains were divided into groups as per their predominant sensitivities to bleach, enzymes and mechanical action according to Table 2. The mean performance of different stain groups is shown in Fig. 4.

In order to see how the contribution of the different stain groups changed, the values of the groups were compared relatively. Since the absolute washing performance of all machines was different, it is difficult to see if the relative contribution of the washing performance of the stain groups change. In order to evaluate this, the sum of all the stains was set to 100% for each compared system, so that only the changes in the contribution of the stain groups to the total performance could be compared.

This led to a very narrow distribution of the relative contribution of the stain groups. The stains sensitive to mechanical action contributed (37 ± 0.7) % to the average luminance, those sensitive to enzymes contributed (28 ± 0.2) %, and the bleach sensitive stains contributed (35 ± 0.5) %. As an example, we looked more into the performances of the

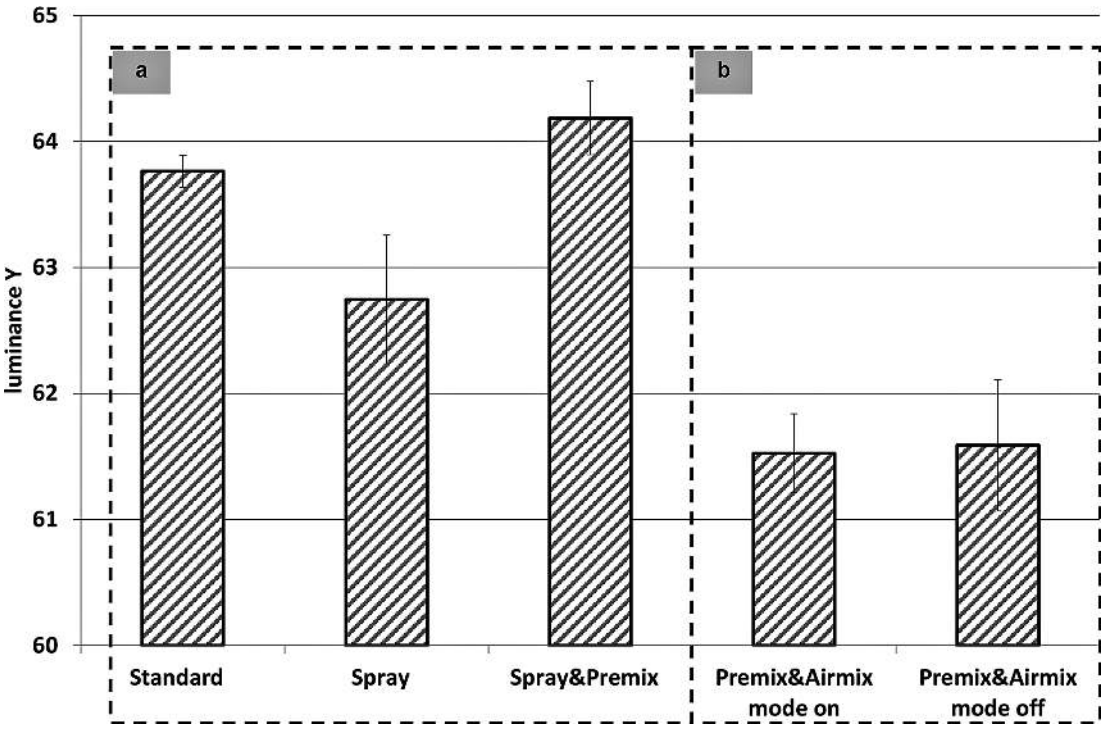


Figure 3 Mean luminance as relative measure of washing performance. a: Systems with long main wash time; and b: Systems with short main wash time. Error bars show confidence intervals at 95%-level

individual stains in the groups of mechanical- and enzyme-sensitive stains.

When the different systems were compared to each other, most of the stains showed no significant differences, which was in line with the small differences of the average values. For the Spray & Premix-System, we could observe two significant differences compared to the Standard-System. In the group of mechanical-sensitive stains, only the removal of Sebum/soot (CS 32 from CFT) was significant, see Fig. 5a. Removal was 3.1 luminance higher than the Standard-System. This kind of stain was also recommended for judging the detergent's builder action [11]. The other stains showed up to differences in luminance of 2, but these differences were not significant. In the group of enzyme-sensitive stains, salad dressing (CS 06 from CFT) was significantly better removed (by 2.8 luminance) compared to the Standard-System (see Fig. 5b). The stain comprised oil, starch and egg yolk, mustard, fruit, thickening agent and preservatives. It should be stated that high agitation was needed to remove this stain [11]. Therefore, it was not only sensitive to enzymes, but also to mechanical action.

4 Discussion

The presence of a circulation system alone could not guarantee that the overall washing performance would be better than the systems without it. This was the case even when similar washing conditions were chosen. For example, the Spray-System performed worse than the Standard-System. This can be explained by the lower performance of mechanical sensitive stains, see Fig. 4. In this special case the performance could be influenced by the high foam level at the beginning of the washing process. The Spray & Premix-System performed slightly better than the other two.

This led to the conclusion that small variations of Sinner Circle parameters such as temperature and washing time, still influenced the performance dominantly as did the parameters such as drum geometry, amount of load, drum rotation speed and internal water flow management that were not considered here in detail.

This conclusion is also supported by the fact that consumer tests generally do not show better performance with circulation systems. But with regard to consumer tests, one has to keep in mind that these tests allow much more different machine parameter settings, and therefore, are not designed to distinguish the influence of single technologies.

The Premix & Airmix-System could not be directly related to the other results as the washing time was much shorter. In this case, only the effect of turning the Airmix on or off could be compared. At the level of stain groups as well as at the level of single stains, no significant differences were found. Even the relative contribution of the stain groups to the overall performance was not different when compared to the other examined systems. Therefore, no drastic change of washing regime was expected by the use of additional air. In order to get a better grasp of the effect of this machine, a second investigation should be carried out so as to differentiate between premixing and the introduction of air into the water flow.

A more detailed look at the stain groups showed that some differences were found predominantly in the class of mechanical sensitive stains. But more generally, the washing performance profile did not change drastically. In the case of the Spray & Premix-System, only two significant differences could be found – the first for a mixture of sebum and soot, and the second for the more complex formulated salad dressing. Since the first stain was also sensitive to the builder system, it was apparent that premixing was likely responsible for this effect. For the second stain, the difference was more difficult to explain, as the effect could be probably due to the combination of longer washing duration and premixing of the enzymes. But as the main wash time for the Spray & Premix-System was about 10% longer than the Standard-System, there remained an uncertainty over

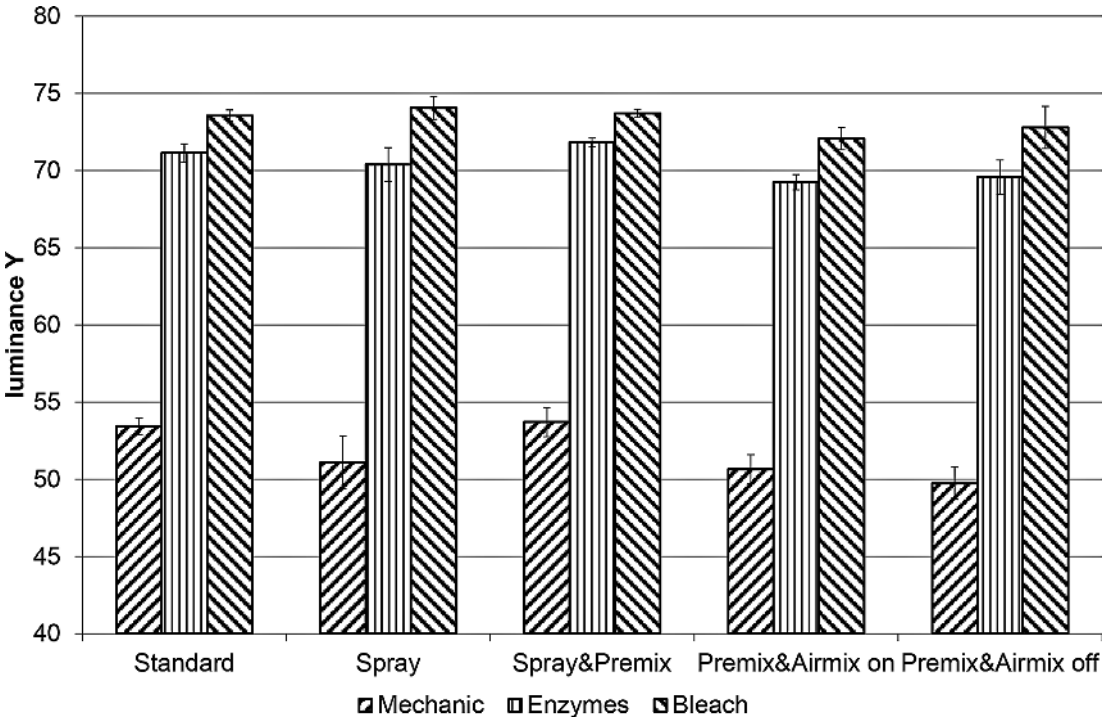
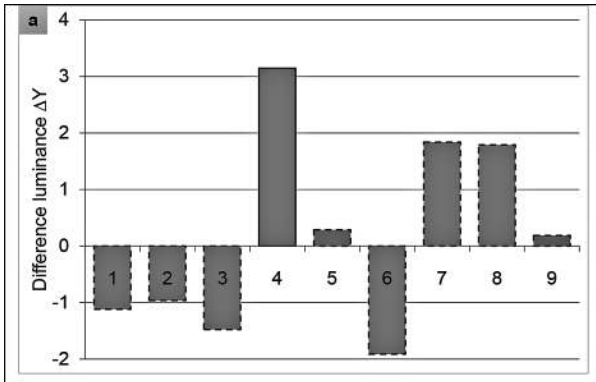
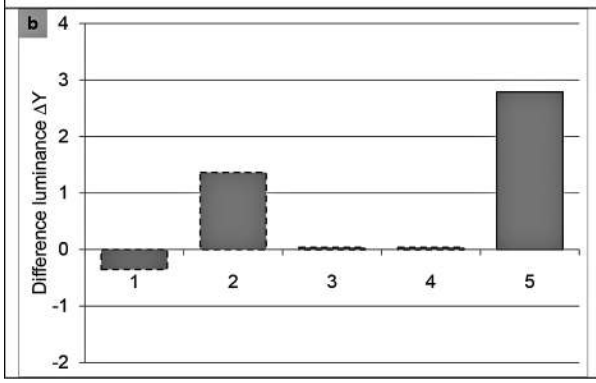


Figure 4 Mean luminance of stain groups as measure of washing performance



Nr.	Type	Stain
1	CFT C01	soot/mineral oil
2	CFT C02	Olive oil/soot
3	CFT C09	Pigment/oil
4	CFT CS32	Sebum/soot
5	WFK 20D	Pigment/sebum
6	CFT CS05S	Mayonnaise/carbon black
7	CFT CS17	Make up
8	CFT CS216	Lipstick red
9	CFT PCS16	Lipstick, pink



Nr.	Type	Stain
1	CFT CS37	Full egg/pigment
2	CFT CS44	Chocolate drink
3	CFT CS26	Corn starch
4	CFT CS28	Rice starch
5	CFT CS06	Salad dressing/ natural black

Figure 5 a: Mechanical sensitive stains, and b: Enzyme sensitive stains. The relative absolute difference of removal as ΔY luminance between the Standard-System and the Spray & Premix-System. Positive values are in favour of the Spray & Premix-System. Solid bar border: significant differences at 95 % level; and dotted: not significant

whether the differences would also be significant for the processes with the same cycle duration. In order to clarify these findings and to differentiate between premixing and spraying, experiments with adjusted washing times should be carried out in a separate investigation.

Therefore, only small differences in the performance of stain removal with regard to different circulation systems could be expected. But these differences were big enough to affect the comparability of detergent testing in different types of washing machines. On the other hand, the magnitude of the differences was only valid for constant detergent and soil concentration. Therefore, different results would be expected if the dosage of detergent was in accordance to the detergent and the machine manufacturer's recommendations.

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