UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL

ESCOLA DE ENGENHARIA

PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA DE MINAS METALÚRGICA E DE MATERIAIS - PPG3M

LABORATÓRIO DE TECNOLOGIA MINERAL E AMBIENTAL - LTM

DESENVOLVIMENTO E VALIDAÇÃO DA TÉCNICA INTEGRADA DE FLOCULAÇÃO-FLOTAÇÃO EM COLUNA (FFC), FILTRAÇÃO EM AREIA E CLORAÇÃO NA RECICLAGEM DE ÁGUA NA LAVAGEM DE VEÍCULOS

TESE DE DOUTORADO

M.Sc. Rafael Newton Zaneti

Porto Alegre

2012

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Rafael Newton Zaneti

Tese apresentada ao programa de pós graduação em engenharia de Minas, Metalúrgica e de Materiais da Universidade Federal do Rio Grande do Sul, como requisito parcial à obtenção do título de doutor em engenharia.

Área de concentração: Tecnologia Mineral, Ambiental e Metalurgia Extrativa

Orientador:

Prof. Dr. Jorge Rubio

Porto Alegre

2012

“Ora, olhando agora para nós todos, penso que se não começarmos a viver desde já como sobreviventes lúcidos e conscientes, amanhã poderá ser tarde demais. Quando os crimes contra o planeta em que vivemos se tornarem irreversíveis, quando o lixo invadir as casas, quando a poluição fizer desta atmosfera um tóxico, quando a destruição das florestas tornar o mundo um deserto, quando os rios e os mares se transformarem em cloacas fétidas, os sobreviventes não sobreviverão”.

José Saramago

Esta tese foi julgada adequada para obtenção do título de Doutor em Engenharia, área de concentração em Metalurgia Extrativa e aprovada em sua forma final, pelo Orientador e pela Banca Examinadora do Curso de Pós-Graduação.

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RESUMO

Técnicas e tecnologias poupadoras de água tem sido objeto de pesquisa no mundo inteiro, principalmente em modalidades urbanas. A presente tese de doutorado contribuiu para o desenvolvimento de um processo inovador descentralizado de reúso de água em ambientes comerciais, tomando como modelo a lavagem de veículos. A reciclagem de água na lavagem de veículos é uma prática que começa a ser intensamente empregada em países do primeiro mundo motivada por exigências legais. No Brasil, somente nas principais cidades, estima-se em 7 milhões de m³ o consumo mensal de água nesta atividade, aproximadamente 0,5% da demanda urbana por água. Mais, o efluente da atividade lavagem de veículos é ainda altamente poluído com surfactantes, nanopartículas e microorganismos, entre outros poluentes. Estes dados justificam o desenvolvimento de uma tecnologia que possibilite a reciclagem adequada de água nesta atividade, com viabilidade técnica e econômica. O presente trabalho desenvolveu, avaliou, validou e transferiu ao setor produtivo um processo baseado na aplicação integrada das técnicas de Floculação-Flotação em Coluna – FFC, filtração em areia e cloração para tratamento e reciclo destes efluentes. As unidades de floculação (floculador hidráulico em linha – tr = 10s, G > 1000s-1; Tanfloc SL - 200-700 mg.L-1) e geração de microbolhas (bombas centrifugas multifásicas – microbolhas com D32 = 75µm) possibilitaram a formação de flocos aerados (0,8–1,6 mm de diâmetro e velocidade de ascensão de 45-150m.h-1) e consequente alta taxa de separação sólido-líquido na coluna de flotação (>18m.h-1). A partir destes dados de caracterização da técnica, um sistema de reciclagem de água na lavagem de veículos de passeio foi instalado e monitorado ao longo de seis meses. Ainda, a técnica FFC foi empregada de forma integrada com a filtração em areia e a cloração (0,5 mgCl2.L-1). A água residuária e a água tratada via FFC+filtro de areia+cloração foram caracterizadas e a eficiência de remoção de sólidos suspensos (>85%), turbidez (>90%), surfactantes MBAS (>40%), DBO5 (>60%), DQO (>60%) coliformes totais (95%) e E.coli (99% - 2 log) determinada. Este estudo longo foi realizado em um lava-rápido comercial em Porto Alegre-RS e uma economia de 70% de água no processo de lavagem foi atingida. Entretanto, embora mais de 2000 carros tenham sido eficientemente lavados com a água

tratada, foi observada uma tendência de aumento de sais dissolvidos, além de uma alta concentração de coliformes, mesma na água tratada. Assim, a quantificação de risco microbiológico (à saúde humana) e de risco químico (agressividade aos veículos e equipamentos – incrustações, manchas e corrosão) fez-se necessária. As metodologias aplicadas foram: o quantitative microbial risk assessment – QMRA e o balanço de massas de parâmetros de interesse. O QMRA mostrou ser necessário se limitar a concentração de E.coli a 200 $NMP.100mL^{-1}$. Esta contagem de microrganismos foi atingida com dosagem mínima de 15 $mgCl_2.L^{-1}$. O balanço de massa proposto mostrou que a água de reúso, após cloração para efetivo controle microbiológico, apresenta concentração de sais e, especificamente, cloretos, em níveis aceitáveis. Quanto à viabilidade econômica, esta ficou confirmada por uma avaliação econômica simplificada que confrontou economia na despesa com água, versus custos de investimento e operação da tecnologia – a depender da demanda por água, o payback pode ser inferior a 6 meses. O pedido de patente da técnica foi depositado em 2008 e publicado na revista do INPI em 03/2010, sob o número PI 0802871-0, sendo a UFRGS a proprietária da técnica. A transferência da técnica à sociedade, por sua vez, foi realizada por diversas publicações em revistas e congressos nacionais e internacionais, bem como pela comercialização da tecnologia, revertendo benefícios à universidade e ao meio ambiente. A efetiva transformação da técnica em tecnologia, na nossa sociedade, somente irá ocorrer caso seja gerado um nicho inicial de mercado que sustente a continua aplicação e desenvolvimento da prática de reciclagem de água na lavagem de veículos. Para tanto, uma moderna legislação especifica deve ser criada e fiscalizada, bem como incentivos financeiros deverão ser estabelecidos. Espera-se que os resultados aqui apresentados sejam um indutor de ambos os processos.

ABSTRACT

Water savings technologies have been a research object around the world, mainly in urban modalities. The present PhD thesis contributes to this theme developing and validating an innovative decentralized water reuse technique in vehicles wash activity. The practice of water recycling/reuse in vehicles wash begins to be intensively employed in developing countries, where laws impose it. In Brazil, this practice is not imposed, but a monthly consumption of 7 millions of m³ (0.5 % of the total urban water demand) and a great pollution load justified such a practice, moreover when new technical and economically feasible techniques are domestically available. Herein, the developed, evaluated, and validated technique is based on the integration of flocculation-column flotation (FCF), followed by sand filtration and chlorination. The claimed advances of the proposed process are: in-line fast and turbulent flocculation/mixing – 10 s and 1,000 s^{-1}, using a tannin based coagulant/flocculant; multiphase centrifugal pump microbubbles generation – generating bubbles with Sauter mean diameter (D_{32}) around 75 µm; appearance of aerated flocs - 0,8 – 1,6 mm equivalent diameter with a rising rate in between 45 – 150 $m.h^{-1}$; and fast solid-liquid column flotation (high hydraulic-load – around 18 $m.h^{-1}$). Following the successful development of the technique, a full scale water recycling system was installed and monitored in a commercial car wash per six month. The car wash wastewater and the treated water (FCF plus sand filtration and chlorination – 0,5 $mgCl_2.L^{-1}$) where characterized and the efficiency in removing suspended solids (> 85%), turbidity (> 90%), surfactant MBAS (> 40%), DBO_5 (> 60%), total coliformes (95%) and *E.coli* (99%) determined. Regarding water consumption, a water audit showed 70% water save – average for 2,000 car washes. Observed drawbacks where the tendency for rising dissolved solids concentration and a still high concentration of *E.coli* in treated water. To better understand and control this drawbacks a mass balance and a quantitative microbiological risk assessment (QMRA) where employed. The answers where: i. Although there is a dissolved solid increment, the risk of vehicles and wash equipment corrosion and scaling are low, or controlled; ii. The microbiological risk of the water reclamation system can be controlled

by limiting the *E.coli* counting in 200 CFU.100mL^{-1}. Once the technical issue is solved, it works to walk trough economics. A simple economic evaluation was performed for different Brazilian state capitals and showed financial viability – depending on water demand and price the payback period can be as low as 6 months. Considering the potential for innovation, the process had it intellectual property (patent) required, being the University - UFRGS the proponent. By now, the technique is being transferred to the market by a great number of national and international publications. Moreover, a small company (an university spin-off) is commercializing the technique. Nevertheless, it seems that an early market must be constructed from public policies, supporting the commercialization and demonstration of the technique. It is well known that public policies, including at least financial incentives and technical regulation, are imperative to turn a technique in a technology (innovation chain). The authors believe that the present work will help in this evolution.

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$A(r)$ – Expanded area of the floc image

r – Radius of the circumference used to expand the image

D_2 – Two dimensional fractal dimension

e – Flux dissipated energy

u – Fluid viscosity

r – Fluid specific weight

d – Flocs average diameter

s– Floc strength

D_{32} – Microbubbles Sauter mean diameter

PARTE I

1. Introdução

A Organização das Nações Unidas - ONU estima em 2.500 m³/hab./ano a taxa de disponibilidade hídrica para a vida em comunidade nos ecossistemas aquáticos e para o exercício das atividades humanas, sociais e econômicas. A escassez de água ou a diminuição da sua disponibilidade, em aspectos de qualidade e quantidade, limita o desenvolvimento sustentável, muitas vezes potencializando conflitos regionais. No Brasil, por exemplo, apesar do expressivo potencial hídrico, o Plano Nacional de Recursos Hídricos (PNRH, 2006), elaborado pelo Ministério do Meio Ambiente – MMA e aprovado pelo Conselho Nacional de Recursos Hídricos (CNRH, 2006) aponta que algumas regiões hidrográficas brasileiras sofrem escassez física (quantidade) de água. Segundo as metodologias da ONU e da *European Environmental Agency* – EEA, estas regiões, que encerram os principais centros urbanos do país, são enquadradas nas classes "preocupante", "crítica" ou "muito crítica" (Tabela 1.1) no que concerne a escassez de água.

Tabela 1.1. Classe de escassez de água em função da divisão hidrográfica nacional – Adaptado de PNRH (2006).

Divisão hidrográfica nacional	Principais cidades	Relação demanda / disponibilidade	Classe
Atlântico Leste	Salvador, Aracaju	22,3%	Crítica
Atlântico Nordeste Oriental	Recife, Fortaleza, Maceió, Natal, João Pessoa, Mossoró, Campina Grande	186,81%	Muito crítica
Atlântico sudeste	Rio de Janeiro, Vitória	15,16%	Preocupante
Atlântico Sul	Porto Alegre, Florianópolis, Caxias do Sul, Pelotas, Joinville	35,77%	Crítica
Uruguai	Chapecó, Uruguaiana, São Borja, Bagé	25,84%	Crítica

Esta situação de escassez crítica ocorre também em algumas sub-regiões hidrográficas, como por exemplo, a região metropolitana de São Paulo-SP, agravada pela baixa qualidade do pouco recurso disponível. Este quadro atual evidencia a necessidade de uma nova abordagem na gestão dos recursos hídricos em ambientes urbanos, que incorpore princípios de sustentabilidade e de produção mais limpa. A água de reúso surge neste contexto como um manancial alternativo, constituindo uma fonte deste recurso em regiões de escassez e de elevado consumo (modalidades urbanas e industriais). Entretanto, os desafios para a aplicação de sistemas de reúso ou reciclagem de água em centros urbanos são grandes e envolvem políticas públicas, infraestrutura, aceitação da população, viabilidade técnica e econômica.

No Brasil, o reúso direto não potável de água é regulamentado pelas resoluções CNRH 54/2005 (modalidades, diretrizes e critérios gerais) e CNRH 121/2010 (modalidade agrícola e florestal). Segundo estas resoluções, a água de reúso é a água residuária que se encontra dentro dos padrões exigidos para utilização nas modalidades pretendidas. Os padrões específicos para as diversas modalidades, entre elas as urbanas, devem ainda ser estabelecidos pelos órgãos competentes.

A lavagem de veículos é uma atividade urbana que utiliza elevado volume de água. O reúso de água nesta modalidade apresenta a possibilidade de instalação de estações de tratamento para reúso de água descentralizadas, *on-site*, diminuindo necessidades de infraestrutura e aumentando viabilidade técnica e econômica.

Um balanço do Departamento Nacional de Transito (DENATRAN) indica que nos últimos dez anos, o aumento da frota nacional de veículos foi de 119%, superando 65 milhões de registros. No exercício 2009/2010, a frota brasileira de veículos cresceu 8,4% e considerando o resultado do Censo IBGE 2010, que indica que a população é de 190.732 milhões, o país tem uma média de 1 (um) veículo para cada 2,94 habitantes.

A efetiva implementação da reciclagem de água na lavagem de veículos necessita de políticas públicas e leis devidamente regulamentadas (embasamento técnico) e impositivas. Entretanto, somente na última década surgiram os primeiros trabalhos técnicos sobre o assunto, que avaliaram diferentes processos (biológicos, sedimentação, flotação e filtração) no tratamento para reúso da água, mas não incluíram monitoramento de sistemas reais de reciclagem de água (Morelli, 2005), muito menos avaliaram o risco microbiológico desta prática. Assim, pesquisa, desenvolvimento e inovação no tema são fundamentais para disponibilizar informações e tecnologia, que possam embasar tecnicamente a regulamentação de leis e decretos e tornar operacionais os sistemas de reciclagem.

O LTM foi contemplado em 2003, nas categorias graduado e graduação, com o prêmio Jovem Cientista: Água – Fonte de Vida, e em 2004 com o Prêmio FINEP de Inovação Tecnologica, a partir do case: Inovação para o Tratamento Otimizado e Reúso de Águas e Efluentes Líquidos Urbanos e Industriais. Os prêmios acima confirmam o know-how e o know-why do LTM em tratamento para reuso de água, principalmente em efluentes contendo emulsões oleosas, íons de metais e particulados. A partir desta experiência, foi iniciada em 1999, a pesquisa de uma solução para reciclagem de água na lavagem de veículos, resultando em 2003 (PI 0006390-8; patente concedida) e em 2008 (PI 0802871-0; patente publicada) em propriedade intelectual para UFRGS. Estas técnicas foram transferidas ao setor produtivo na forma de diversas publicações em periódicos e congressos de alto impacto, no Brasil e no mundo. Mais, duas empresas *spin-off* do LTM comercializam hoje as técnicas desenvolvidas e revertem royalties à universidade.

1.1. Objetivos

1.1.1. Objetivo geral

O objetivo desta tese é disponibilizar, a partir de estudos básicos e de campo, uma técnica e uma metodologia para tratamento e reúso de água, utilizando como modelo a atividade de lavagem de veículos. As metas técnicas eram a validação do conjunto de métodos e processos proposto e a indicação de parâmetros de qualidade para a água reciclada na atividade proposta, bem como a transferência do conhecimento gerado e de recursos humanos ao setor produtivo.

1.1.2. Objetivos específicos

Os objetivos específicos são os seguintes:

- Desenvolver uma técnica de floculação-flotação, seguida de processos complementares, compacta e de simples operação;
- Avaliar e validar a técnica proposta em um sistema modelo real - lavagem de veículos;
- Estudar a qualidade de água de reúso na atividade de lavagem de veículos - Aspectos i. Estético (clarificação e cor), ii. Microbiológico e iii.Químico;
- Definir uma metodologia de avaliação de risco microbiológico da prática de reúso na atividade proposta;
- Definir uma metodologia para avaliar de risco químico para a prática de reúso na atividade proposta;
- Estimar a relevância da pratica de reúso de água na lavagem de veículos na gestão dos recursos hídricos em ambientes urbanos no Brasil;
- Discutir a cadeia de inovação da técnica proposta na atividade de lavagem de veículos – Políticas públicas e avaliação econômica;

- Transferir o conhecimento adquirido e recursos humanos ao setor produtivo e a sociedade.

1.2. Plano de tese

Esta tese é apresentada na forma de artigos científicos, publicados em periódicos internacionais e está organizada em três Partes**,** cada uma sendo constituída pelos seguintes itens:

Parte I: Introdução, Objetivos geral e específicos e Integração de artigos;

Parte II: Artigos Científicos - Cada artigo científico representa um Capítulo, sendo dividido em, no mínimo: Introdução, Materiais e Métodos, Resultados, Conclusões e Referências Bibliográficas;

Parte III: Considerações finais, Conclusões, Sugestões para trabalhos futuros e Bibliografias;

Os trabalhos elaborados e realizados durante esta tese foram desenvolvidos no Departamento de Engenharia de Minas da UFRGS, no Laboratório de Tecnologia Mineral e Ambiental, e em campo - em uma empresa de ônibus que opera o transporte público coletivo e em uma lavagem comercial de veículos, em Porto Alegre/RS.

2. Integração dos artigos científicos

A presente tese é uma ação de P&D&I na linha de pesquisa de tratamento e reciclagem de água em modalidades urbanas. Os principais avanços e metas técnicas do trabalho foram: i. O desenvolvimento e a caracterização de uma inovadora técnica de floculação-flotação, a Floculação-Flotação em Coluna (FFC) para reúso de efluentes urbanos em unidades descentralizadas de tratamento; ii. A validação desta tecnologia em campo, em escala real, na atividade proposta; iii. A indicação da qualidade necessária á água de reúso na atividade proposta, atentando especialmente para os aspectos estéticos, risco químico (aos veículos e equipamentos de lavagem) e microbiológico (a saúde dos operadores) da prática; iv. a transferência do conhecimento adquirido ao setor produtivo, a partir de processo de patenteamento da técnica FFC, publicações e apresentações em periódicos e congressos nacionais e internacionais; v. Discussão acerca da cadeia inovativa da técnica, incluindo avaliação econômica. Estas metas técnicas foram os objetos das publicações internacionais realizadas e a integração destes artigos científicos alcança o objetivo geral proposto para esta tese. Alguns tópicos pertinentes ao assunto desta tese são discutidos nos Apêndices, uma vez que não foram trabalhados em profundidade.

2.1. Desenvolvimento e Caracterização da Floculação-Flotação em Coluna

O reuso de água no local de geração do efluente apresenta uma série de vantagens, principalmente em ambientes urbanos. A indústria e o setor de serviços podem ser beneficiados, com redução de custo e maior sustentabilidade de sua operação.

Processos físico-químicos são aplicados no tratamento de efluentes, entregando água clarificada. A Floculação seguida de flotação é empregada no tratamento de suspensões leves de óleos, graxas, fibras e material particulado. Efluentes com estas características ocorrem em processos de lavagem (roupas, veículos e na produção de alimentos). O desenvolvimento de uma técnica de floculação-flotação, compacta e de alta eficiência de clarificação de efluentes, é de alto interesse ambiental e econômico.

O *Know-how* e o *Know-why* do LTM nas áreas mineral e ambiental entregam diversos frutos à indústria nacional nestes mais de 30 anos, destaque para as patentes nas áreas de remoção de amônia (PI 0406319-8), recirculação de água de lavagem de veículos (PI 0006390-8) e geração de flocos (PI 0406106-3). Nesta tese, uma nova técnica de floculação-flotação é proposta, a Floculação-Flotação em Coluna (FFC).

O primeiro artigo científico traz o desenvolvimento e a caracterização desta nova técnica. Busca-se aumentar a compacidade e facilitar a operação, em relação a floculação-flotação convencional. Tempo, geometria e grau de agitação são avaliados no processo de floculação. A separação sólido/líquido é avaliada quanto à taxa de aplicação hidráulica e altura da coluna de flotação. Os resultados são discutidos a partir da caracterização dos flocos e das microbolhas presentes.

2.2. Validação da tecnologia FFC em campo, em escala real, no tratamento e reciclagem de água de lavagem de veículos

Os resultados iniciais obtidos no desenvolvimento e caracterização da tecnologia FFC mostram seu potencial. O objeto deste segundo artigo científico é a aplicação do processo FFC no tratamento para reciclagem de água de lavagem de veículos, em um sistema real. Os estudos são desenvolvidos em um típico serviço de lavagem de carros (veículos de passeio) brasileiro, na cidade de Porto Alegre/RS. O processo FFC é empregado de forma integrada, com a filtração em areia e a cloração.

São monitorados (durante 20 semanas) o uso e as características da água reciclada. A determinação do percentual de economia de água potável e a possível ocorrência de acumulo de poluentes no sistema, assim como de risco a saúde humana, aos veículos e aos equipamentos de lavagem são avaliados. Ainda, uma avaliação econômico-financeira foi realizada, com base no custo de água em Porto Alegre-RS e em São Paulo-SP

2.3. Análise de riscos químicos e microbiológicos na reciclagem de água na lavagem de veículos

A viabilidade técnico-econômica da prática proposta motiva a continuidade da pesquisa. Entretanto, a elevada contagem de coliformes (*E.coli* e totais) e o incremento da concentração de sais dissolvidos no efluente da lavagem de veículos, observados ao longo das 20 semanas iniciais de monitoramento do sistema em campo, motivam a avaliação dos riscos químicos e microbiológicos aos seres humanos, veículos e equipamentos envolvidos.

Este terceiro artigo científico apresenta a realização de estudos em bancada e do tratamento dos dados obtidos em campo. O risco microbiológico, oferecido aos clientes e operadores da lavagem, é avaliado a partir do emprego da metodologia *Quantitative Microbial Risk Assessment* - QMRA, enquanto o risco químico, oferecido aos veículos e equipamentos de lavagem, a partir de balanço de massa de parâmetros de interesse.

Ainda, uma discussão econômico-politica é realizada, abordando a estimativa do impacto da reciclagem de água de lavagem de veículos na gestão dos recursos hídricos urbanos das principais capitais brasileiras, as legislações existentes no mundo e no Brasil no tema do trabalho e a cadeia de inovação da técnica proposta.

PARTE II

TREATMENT OF WASHRACK WASTEWATER WITH WATER RECYCLING BY ADVANCED FLOCCULATION–COLUMN FLOTATION

Artigo publicado no periódico Desalination and Water Treatment, Volume 8, 2009, Páginas 146-153

3. Treatment of washrack wastewater with water recycling by advanced flocculation–column flotation

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Abstract

A new technique of flocculation (aerated flocs), called column flotation (FCF) was evaluated in the treatment of vehicles (bus) wash wastewater and water reuse. The technique is composed of a compact flocculation - flotation unit, utilizing an in-line flocculator device, a centrifugal multiphase pump which generates microbubbles (Sauter mean diameter, 75 μm) and a column flotation for the solid/liquid separation. Design and operating parameters were studied and the efficiency of the FCF was evaluated by the chemical and physio-chemical quality of the treated water. A tannin derivative was employed as a flocculant and aerated flocs (0.8-1.6 mm diameter; 45-150 $m.h^{-1}$ rise rates) were rapidly formed (10 s, residence time). Because of the rapid formation of these very light flocs, the FCF showed a high hydraulic-load capacity (>18 $m.h^{-1}$), low foot print area (compact unit), and low energy consumption. It is believed that this rapid flocculation-column flotation system appears to have a high potential for oily (or not) voluminous effluents treatment at high flow-rates.

Keywords: Flotation, Flocculation, Water reuse, Aerated flocs

3.1. Introduction

Flocculation and flotation processes were originally designed (in the mining and metallurgical areas) to separate one particle type from another whose density is lower or has been made lower than the suspending liquid. However, there have been rapid developments of devices and techniques of flocculation followed by flotation being applied in drinking water plants and in many wastewater treatments (Rubio et al., 2007).

Buses, trucks, big and small vehicles, and machine washing processes use a large amount of water worldwide. In Brazil alone, more than 4 million cubic meters of water are used in this activity every month, which is equal to the water consumption of a city with 600,000 inhabitants (Rubio et al., 2007). Moreover, the wastewater produced by this activity presents elevated toxicity (Brasino and Dengler, 2007) and causes water pollution. Fortunately this scenario has already started to change, due to the pressure of constant water shortages, increasing water prices and environmental laws.

The stages of pre-soak (automated nozzle or hand held spray), bodywork washing (with high pressure sprays or brushes with or without detergent); rocker panel/undercarriage washing (brushes or high pressure sprays on the sides and underneath of vehicles); first rinse (a high pressure rinse); wax and sealers (a surface finish which is sprayed on the vehicle); final rinse (a low pressure rinse) and hand or mechanical drying are all part of a professional vehicle wash. Brown (2000), has written a report for the international car wash association regarding water conservation in the professional car wash industry. According to this author, reclaimed water can be used in all stages of professional car wash, except final rinse, where fresh or spot free water (TDS lower than 350 – water treated with RO) is recommended.

The reuse water quality is not well defined, but the main concerns relate to problems to the vehicles and washing machines, and exposure of the operators and users to any microbiological risk. With respect to health and safety, Hamada and Miyazaki (2004) show that there was no presence of hazard bacteria or E. Coli., in car wash recycling systems.

In vehicles, the following wash water recycling techniques have all been proposed and tested: reverse osmosis and nanofiltration (Brown, 2000); ultrafiltration Jönsson and Jönsson, 1996); ultrafiltration-activated coal adsorption (Al-odwani et al., 2006); biological treatment; biological treatment-flotation; flocculation-sedimentation and flocculation-dissolved air flotation (DAF). Nevertheless, some of these processes are expensive (investment, operation and maintenance) and/or demonstrate poor efficiency, and often require large foot-print areas.

Rubio et al. (2002) reviewed flocculation-flotation techniques and their applications and in a recent work, Rubio et al. (2007), show the application of the flocculation-flotation in the vehicle wash wastewater treatment for water recycling. Advantages claimed were: low maintenance and operational costs (low reagents costs and a single unskilled operator required) plus moderate investment costs; reduced foot-print area; and high water clarification (more than 85% turbidity reduction). According to these authors, up until 2007, the process has recycled up to 400,000 m^3 of water in more than 20 units operating in Brazil. The first generation scheme, named ETAR, consisted of flocculation in two stages (an in-line hydraulic flocculator (FF) to rapid mixing and an agitated tank to slow mixing) followed by flotation in a DAF cell (hydraulic-load is 9 $m.h^{-1}$).

FF and Flocs generation reactor – FGR® are in-line facilities which use the flux kinetic energy and plug-flow mixing for flocs generation. Carissimi and Rubio(2005) described the FGR® development studies and Rosa and Rubio (2005) presented the FF flocculator. These authors believe that these devices can work as bubbles/flocs contactors creating the so-called aerated flocs.

Aerated floc formation mechanisms are not yet well understood and their characterization (size, rise rates, strength and fractal dimension) as well as their entrapped bubbles diameter and air volume must be fully studied to assist the flocculation-flotation process, control and design.

Column flotation is broadening its applications in the environmental area, such as in the treatment of oil and grease, metallic ions, de-inking, and suspended solids removal (Finch, 1994; Filippov et al., 2000; Caponni et al., 2006). Its high throughput and its flux pattern (plug flow), are their main advantages.

This work is a continuation of a series of papers on development, basic principles and application of advanced flocculation followed by flotation. The aim of this work was to apply and evaluate a new flocculation-flotation unit for the treatment and water reuse, named Flocculation – Column Flotation (FCF). Another aim was to provide some data on the rapid formation and characterization of aerated floc.

3.2. Materials and methods

The experimental work was carried out in a Metropolitan Transportation Bus Company (a 250 bus fleet site), located in Porto Alegre, South Brazil. The company installed a flocculation-flotation unit (ETAR) followed by a sand filter in 2004 for the treatment and recycling of the fleet wash wastewater.

3.2.1. Wastewater and reagents description

The studied wastewater which passed through an API oil separator was collected via gutters in the bus wash site. The buses had their chasses, bodywork, wheels, and mechanical components washed. Wastewater characteristics showed some variations during the experimental investigation, which poses some problems (separation efficiency), but this is typical of a practical and real system (Table 3.1). Table 3.1 shows the wastewater characteristics, which were close to those found in wash waters from metallurgical, petrochemical and petroleum industries.

The reagents employed were: Tanfloc SL (a tannin based low molecular weight polymer) in the concentration of 200-700 $mg.L^{-1}$ (depending on the effluent characteristics) and Na(OH) for pH adjustment.

Table 3.1. water composition: Main parameters. Number of sample: 30.

Parameter	Mean Value*
pH	7±0,2
Turbidity, NTU	139±45
Color, Hz	217±35
Hardness, $mg.L^{-1}$ $CaCO_3$	168
Surface Tension, mN.m	31±1
Conductivity $uS.cma^{-1}$	446±55
Total Solids, $mg.L^{-1}$	543±25
Dissolved Solids, $mg.L^{-1}$	452±30
Suspended Solids, $mg.L^{-1}$	112±21
Oils and grease, $mg.L^{-1}$	12±6
COD, $mg.L^{-1}$	259±40
TC, $mg.L^{-1}$	45±3
TOC, $mg.L^{-1}$	20±5

* Mean = ± ½ Standard deviation

3.2.2. Aerated floc characterization

Aerated flocs characterization was made in-line. According to Owen et al. (2008), mechanically stirred vessels and off-line measurements present several problems for floc analyses.

The flux exiting an in-line pilot-scale flocculation and microbubbles generation unit, fed a bench scale column flotation device, whereby a graduated cell connected at the top allowed for an individual view of the aerated floc. Therefore, the measurement of the flocs rise rate (more than 50 flocs were evaluated) was possible and their equivalent air bubble diameters were estimated using the Stokes law (Carissimi and Rubio, 2005; Rodrigues and Rubio, 2007). Digital images were captured, and the aerated floc equivalent diameter, fractal dimension, and theoretical strength were estimated.

The Boulingand-Minkowski or Minkowski dimension (equation 1) is a method of determining the fractal dimension which creates a relation between the expanded area (A) of an image and the radius (r) of the circumference used to expand this image. The method gives a two dimensional fractal dimension (D_2) (Cetera, 2001). Each floc (around 10 flocs) image had its area expanded with three different radius circumferences (0.5, 1 and 2 pixels).

$$D_2 = 2 - \lim r_{\to 0} \frac{\ln(A(r))}{\ln(r)} \quad (1)$$

Jarvis et al. (2005) and Li et al. (2007) present the theoretical method for floc strength calculation (equation 2) as a function of flux dissipation energy (ε), fluid characteristics (viscosity (υ), specific weight (ρ)) and flocs average diameter (d). The average strength per unit area at the plane of floc rupture is defined as σ (N/m²).

$$\sigma = 2.31 \frac{\rho.\varepsilon^{3/4}.d}{\nu^{1/4}} \quad (2)$$

3.2.3. Microbubbles characterization

A multiphase (water/air) pump was employed for the bubbles generation. The pump receives the air at the inlet (suction), and then shears it within the impeller. Thus, an efficient and fast air in water dispersion and dissolution was achieved in the pump outlet, rapidly reaching solution saturation, with the microbubbles being formed after passing by a nozzle (needle-valve).

The microbubbles generated in the recycling current (FCF treated bus wash wastewater) were measured (in the laboratory) using the LTM-BSizer device (Rodrigues and Rubio, 2003). The Sauter mean diameter (D_{32}) of the distribution was employed as the main size parameter.

3.2.4. FCF studies

A FCF pilot-scale ($1m^3.h^{-1}$) unit (Figure 3.1) was installed in parallel with the Bus Company water recycling equipment (ETAR). The FCF equipment had its flocculation unit characteristics varied, i.e.: reactors geometry, retention time, and mixing intensity (Table 3.2 shows their hydraulic characteristics).

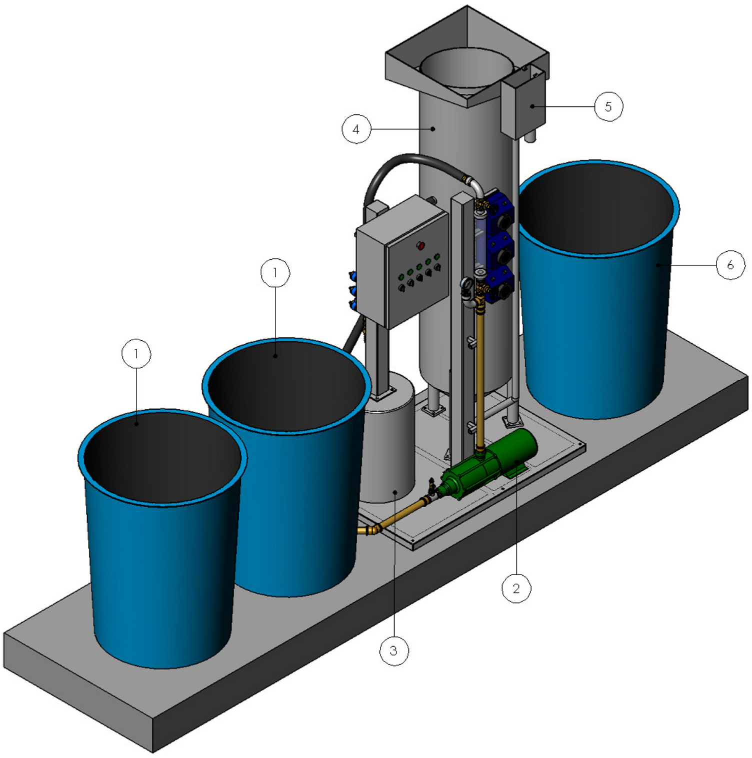

Figure 3.1. The FCF unit. 1 – Wastewater equalization tank, 2 –Multiphase Centrifugal Pump, 3 –FGR® – Flocs Generator Reactor, 4 – Column Flotation, 5 – Level control, 6 – Treated water tank.

Table 3.2. Hydraulic and hydrodynamic characteristics of in-line hydraulic flocculators.

Reactor		Rapid Mixing (RM)		Slow Mixing (LM)		Camp
RM	LM	[a]Rt, s	[b]G, s^{-1}	Rt, s	G, s^{-1}	number
FGR®	-	17	1350	-	-	22650
FF 1	-	10	1025	-	-	10250
FF 1	FGR®	10	1025	17	1350	32900
FF 1	FF 2	10	1025	180	50	19250

[a]Rt – retention time; [b]G – velocity gradient

FGR® (Carissimi and Rubio, 2005), the flocs generator reactor and FF (Rosa and Rubio, 2005), the flocculation-flotation process were developed at our laboratory. The main characteristics and advantages of these in-line mixing facilities instead of agitated tanks are: no need for moving parts; plug flow (less short circuits and dead zones); low volume/retention times (Camp-number - Ca), and low foot-print areas (Grohmann et al., 1981).

The column flotation was evaluated in terms of hydraulic-load capacity and height required. The column flotation constituent modules were each 0.24 m in diameter and 0.6 m high and were made of acrylic. Column hydraulic connections were made of PVC and their fixtures were made of stainless steel.

Feed was placed at approximately two thirds of the way down from the column top using a 100 mm inner diameter PVC tube with its open end turned up. No contact (bubbles/flocs) zone was included within the column.

The operational characteristics of the microbubbles generation unit were maintained at a constant rate (recycle rate = 30 %, air flow rate = 900 $mL.min^{-1}$ and saturation pressure = 4.5 $Kgf.cm^{-2}$).

The experiments lasted two hours, whereby aliquots of the treated wastewater were sampled every 15 minutes, and were duplicated over different days. Treated water samples had their turbidity, color, conductivity, and surface tension analyzed and the results were statistically treated according to the ANOVA One-Way methodology described in Montgomery (1991).

Validation experiments (2 runs - 4.5 hours last sampled every 30 minutes) were carried out in the FCF optimized configuration, and a comparison between this new system and the old ETAR system were performed (water samples from the ETAR system were collected before sand filtration). The water sample qualities were evaluated by the analysis of solids (total, dissolved, and suspended), TC, TOC, COD, turbidity and color.

All water analyses followed the Standard Methods for the Examination of Water and Wastewater (APHA, 1995).

3.3. Results and discussion

3.3.1. Microbubbles characterization

The bubbles show a diameter of up to 250 μm (Figure 3.2), which characterizes them as microbubbles. The bubbles population mean Sauter diameter (D_{32}), is about 75 μm (a rise rate of 11 $m.h^{-1}$), somewhat higher than the microbubbles generated with pressure vessel D_{32} = 60 μm in DAF (Rodrigues and Rubio, 2003; 2007). Yet, bubbles population average (arithmetic) diameter is about 30 μm (a rise rate of 2 $m.h^{-1}$). According to Kracht et al. (2008), this Sauter mean diameter, a statistical diameter which represents the bubbles size distribution (in volume and surface area), is the most important parameter employed to evaluate gas dispersion (surface flux - Sb, for example) in flotation (mineral particles) devices.

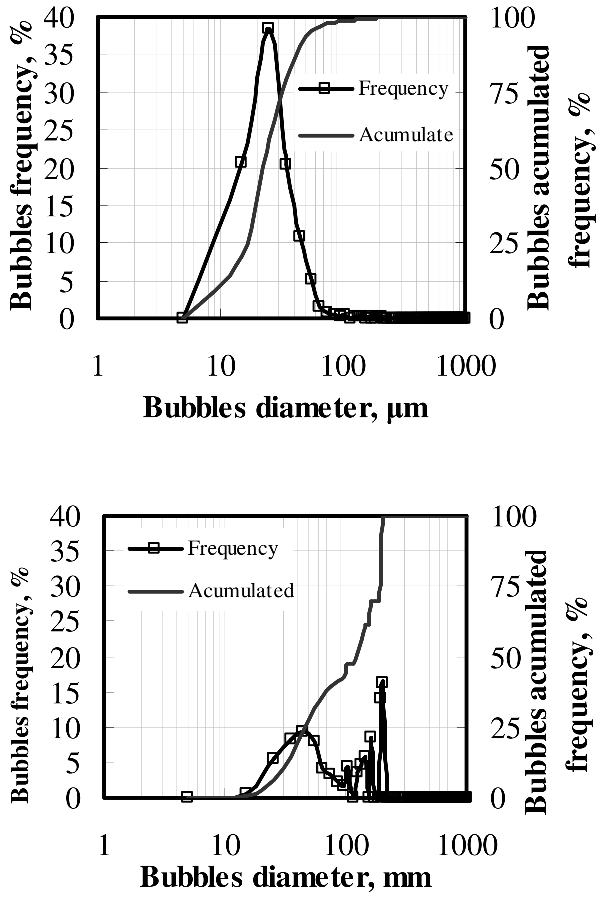

Figure 3.2. Bubbles size distribution. Conditions: FCF treated water; water surface tension = 50 mN.m; water feed rate = 4 L.min-1.; air flow rate = 100 mL.min-1.; saturation pressure = 4 Kgf.cm^{-2}.

3.3.2. Aerated flocs Characterization

The equivalent average diameter and theoretical strength of the flocs formed in two different reagent concentrations are shown in Table 3.3. An increase in reagent concentration allows for a significant flocs growth, and results are in agreement with other studies (Jarvis et al., 2005; Li et al., 2007). The explanation is that, the higher the flocculant concentration, the larger the number of polymer bridges.

Li et al. (2007) show a theoretic floc strength of σ = 0.24 $N.m^{-2}$ for kaolin/aluminum sulfate coagula and Yeung e Pelton (1997) σ = 1 000 $N.m^{-2}$ to calcium carbonate/high molecular weight flocs. Herein, flocculation was assisted by the utilization of a low molecular polymer (tannin base). Therefore, it was expected that the formation of flocs to be stronger than aluminum sulfate coagula, but weaker than those formed in the presence of high molecular polymer.

Table 3.3. Aerated flocs characterization. Floc strength and diameter, as a function of flocculant concentration.

Flocculant concentration ($mg.L^{-1}$)	300	700
Average diameter (μm)	857	1603
σ ($N.m^{-2}$)	49	92

The aerated flocs formation mechanisms are not fully defined, but according to (Rosa and Rubio, 2005), aerated flocs are formed only in the presence of high molecular polymer. Figure 3 shows the (average > 90 $m.h^{-1}$) flocs rise rate, which suggests that several bubbles are inside the flocs. Thus, for any particular flocs velocity, an equivalent bubble diameter has to exist to attain such a rate. In all cases, these "equivalent" diameters are higher than those of the microbubbles and this can only be explained by the entrapment and entrainment phenomena (Rubio et al., 2002; Carissimi and Rubio, 2005; Rosa and Rubio, 2005; Rodrigues and Rubio, 2007).

The flocs average fractal dimension (D_2) was found to be approximately 1.64. Therefore, the flocs are considered to be compact and spherical (Rajat et al., 2000). Otherwise, high D_2 can be related to flocs that had experienced superficial erosion in their formation (Parker et al., 1972; Yeung and Pelton, 1997). This superficial erosion is responsible for a decrease in flocculation efficiency, once that polymer absorption and conformation in the particles surface, and flocs rupture (breakage) then appears to be irreversible (Xiang and Somasundaran, 1996; Owen et al., 2008).

3.3.3. FCF studies

FCF in-line flocculators studies (Table 3.4) show that despite the wastewater characteristics, fluctuation changes, and all mixing devices employed, a clear reduction of the solution turbidity and color can be observed.

Table 3.4. FCF treated water quality as a function of different in-line flocculators. Conditions: [Tanfloc SL] = 300-700 mg.L^{-1}; pH = 7 ± 0.1; Hydraulic-load = 25 m.h^{-1}; Column flotation height = 3.6 m.

Flocculators	Turbidity		Color		Surface tension	
	Reduction,%	NTU	Reduction,%	Hz	Increase,%	mN.m
Bus wash wastewater	-	44-96	-	135-217	-	28-36
FF 1	91	6	73	43	31	40
FGR®	85	8	71	48	36	41
FF1 + FGR®	86	6	68	60	30	42
FF1 + FF 2	92	8	81	42	29	37

Surfactant substances removal was not so pronounced, and treated water surface tension remains below 45 mN.m. Yet, this low surface tension allows for an easy microbubbles generation (Féris et al., 2001) and can diminish the use of soap. The FF 1 alone was selected as the best, because it has the lowest volume/retention time and Camp number, and therefore requires less energy transfer. Furthermore, its treatment efficiency is equal to or higher than other devices.

Column flotation hydraulic-load studies (Table 3.5) shows that turbidity reduction was found to be clearly dependent on process hydraulic-load and when the flux mean superficial velocity inside the column was greater than 25 m.h^{-1}, flocs were dragged toward the clarified current. The highest turbidity reduction was observed at the loading capacity of 18 m.h^{-1} (Table 3.5).

FCF column flotation height studies (Table 3.6) show that the decrease in the column height from 3.6 to 1.8 m improves the FCF treatment efficiency. This result may be due to the better flocs-bubbles contact after decreasing the height/diameter ratio while keeping the superficial air velocity constant.

Table 3.5. FCF treated water quality as a function of different hydraulic-load. Conditions: [Tanfloc SL] = 300-700 mg.L-1; pH = 7 ± 0.1; Flocculator = FF1; Column flotation height = 3.6 m.

Hydraulic-load	Turbidity		Color		Surface tension	
	Reduction,%	NTU	Reduction,%	Hz	Increase,%	mN.m
Bus wash wastewater	-	68-80	-	150-220	-	27-35
9	92	6	79	60	25	41
18	94	6	76	61	27	41
25	88	7	70	65	30	38
33	-	302	10	200	-	-

Table 3.6. FCF treated water quality as a function of different column height. Conditions: [Tanfloc SL] = 300-700 mg.L^{-1}; pH = 7 ± 0.1; Flocculator = FF1; Hydraulic-load = 25 m.h^{-1}.

Column height, m	Turbidity		Color		Surface tension	
	Reduction,%	NTU	Reduction,%	Hz	Increase,%	mN.m
Bus wash wastewater	-	60-95	-	30-190	-	32-28
3.6	87	6	59	60	50	41
3.0	88	6	40	61	32	41
2.4	90	7	33	65	32	38
1.8	93	7	42	61	40	-

3.3.4. FCF and ETAR system comparison

The ETAR plus sand filtration system has been in use for more than 3 years in the Metropolitan Transportation Company without any operational difficulties (even without a final rinse with fresh water). Therefore, it might be stated that ETAR treated water quality suits the bus wash purpose.

Comparative results between the old ETAR and the new FCF system are shown in Table 3.7. The main differences are related to the FCF higher loading capacity and most of the water quality parameters, considering their fluctuations, are much closer.

Finally, other advantages of this new FCF system in treating this effluent are the following:

- The elimination of stirred tanks at the flocculation stage and the substitution by an in-line flocculator leading to less energy consumption and maintenance;
- The use of the multiphase pump makes the microbubbles generation unit safe and easy to operate when compared to broadly used saturator vessels. Yet, there is a decrease in the the microbubbles generation unit control needs and the microbubbles generated are slightly bigger, allowing for flotation kinetics enhancement, while flocs breakage and/or collision difficulty are not observed.

Table 3.7. FCF validation runs. Conditions: [Tanfloc SL] = 500 $mg.L^{-1}$; pH = 7 ± 0.1. Number of samples: 18.

Water	TS, $mg.L^{-1}$	TSS, $mg.L^{-1}$	TDS, $mg.L^{-1}$	TC, $mg.L^{-1}$	TOC, $mg.L^{-1}$	COD, $mg.L^{-1}$	Turbidity, NTU	Color, Hz
Bus wash wastewater	643±70	160±30	456±23	45±3	20±5	259±40	198±25	308±51
ETAR treated water[a]	450±37	11±3	433±40	62±3	33±3	241±23	13±2	65±16
FCF treated water[b]	526±60	12±2	514±54	65±3	35±5	231±35	10±4	62±9

[a]Hydraulic load – 9 $m.h^{-1}$; [b]Hydraulic load – 25 $m.h^{-1}$

3.4. Conclusions

A FCF system was tested and evaluated treating bus wash wastewater and showed high hydraulic-load (>18 $m.h^{-1}$) and water turbidity and color reduction. In regards to water reuse, FCF treated water, seems to suit the bus wash purpose. The aerated flocs formed in the presence of Tanin base flocculant and microbubbles (Sauter mean diameter of 75µm) within the in-line rapid flocculator (retention time equal to 10 s) presented rise rates greater than 45 $m.h^{-1}$ allowing prompt solid/liquid separation.

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CAR WASH WASTEWATER RECLAMATION. FULL-SCALE APPLICATION AND UPCOMING FEATURES

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4. Car wash wastewater reclamation. Full-scale application and upcoming features

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Abstract

Recent features on car wash wastewater reclamation and results obtained in a full-scale car wash wastewater treatment and recycling are reported. The technique employed comprises a new flocculation-column flotation (FCF), sand filtration and final chlorination. Water usage and savings audits (20 weeks) showed that almost 70 % reclamation was possible, and less than 40 L of fresh water per wash was attained. Wastewater and reclaimed water were fully characterized by monitoring chemical, physicochemical and biological parameters. Results were discussed in terms of reclamation aesthetic quality (water clarification and odour), health (pathological) and chemical (corrosion and scaling) risks. Noteworthy, this work showed a high count of faecal and total coliforms both in the wastewater and in the treated water, making the need of a final disinfection mandatory. The cost-benefit analysis shows that, for a car wash wastewater reclamation system in Brazil, at least 8 months were needed for the FCF-SC equipment amortization, when considering a demand over 30 washes per day. It is believed that the discussions on car wash wastewater reclamation criteria may assist alerting wash cars units and institutions to create laws in Brazil and elsewhere.

Key words: Water reuse, in-line flocculation, tannin, flotation, column, disinfection

4.1. Introduction

The car wash industry appears today to be more conscious of the need for wastewater treatment and water reclamation. Worldwide environmental legislation and guidelines concerning this specific issue have been released. Examples show that in Queensland, Australia, it is mandatory the use of at most 70 L of fresh water in a single car wash, and in Europe some countries restrict the water consumption to 60 – 70 L per car and/or impose reclamation percentage (70 – 80 %) (QWC, 2008[a,b]; Boussu et al., 2006).

Reclaimed (reuse, recycling) water is here defined as the wastewater that has gone through various treatment processes to meet specific water quality criteria– *fit for purpose* principle (Metcalf & Eddy, 2006). Although some research effort has been made (Figure 4.1) and distinct technologies have been tested/employed, there are no well defined (accepted) criteria for the quality of car wash reclaimed water yet.

The development of an overall criterion (with sound scientific regulations/standards) should establish limits related to specific practices which would minimize detrimental effects without affecting the benefits. Approaches vary between high technology/high cost/low risk and low technology/low cost/controlled risk (Anderson et al., 2001). Nevertheless, compliance with public acceptance is imperative. Jefferson et al. (2004) reported aspects of public acceptance for urban water recycling in the UK. Their research revealed a broad willingness to accept urban wastewater recycling as long as public health is not affected. Regarding car wash application, results demonstrated that low turbidity is fairly acceptable considering aesthetic characteristic.

According to Brown (2000), car wash wastewater reclamation requires the separation of grit, oils and greases prior to be reused. Additional treatment processes can be employed to strength the usefulness (quality) of reclaimed water to be used in the different washes stages (pre-soak, wash, rocker panel/undercarriage, first rinse, and final rinse). Some of these process/technologies that have been proposed and tested are: reverse osmosis and nanofiltration (Brown, 2000; Boussu et al., 2006); ultrafiltration (Jönsson and Jönsson, 1996); ultrafiltration-activated coal adsorption (Hamada and Miyazaki, 2004);

electrochemical oxidation (Panizza and Cerisola, 2010) biological treatment; flocculation-sedimentation and flocculation-flotation (Rubio et al., 2007).

Some of these alternatives are fairly costly (investment, operation and maintenance), often require large foot-print, and/or show poor efficiency. Flotation has shown advantages and appears to broad its potential amongst these technologies. Surprisingly, not many studies include disinfection processes and the analyses of coliforms in the recycled water.

Table 4.1. Summary of reported research on car wash treatment-reclamation.

Almeida et al., 2010	The study compares three bus-washing systems operating in São Paulo - Brazil. Two were conventional washing, and one was a rainwater harvesting system together with a treatment plant for water reuse. The environmental costs and benefits were estimated, and potential improvements were evaluated using energy accounting; a technique which incorporates the value of nature in human's economy.
Ghisi et al., 2009	The potential for potable water savings by using rainwater for car washing in petrol stations in Brasília, Brazil, has been assessed. It was observed that the average potential for potable water savings by using rainwater was about 33%, fluctuating from 9 to 57%.
QWC, 2008a,b	The Queensland Water Commission released The Vehicles Washing Water Efficiency Guidelines. This guidelines serves as a definition of best practices at long times; providing information on industry water targets, practices and water efficient equipment for specific tasks. A target of maximum 70 and 100 L of potable water is imposed for washing small and large vehicles respectively.
Brown, 2002	The International Carwash Association (USA) assess both, water usage (including the impact of evaporation and carryout) and water reclamation. Maximum water reclamation amounted to nearly 82 % and the ranged between. Carryout plus evaporation was 24.0 ± 17.4% (water losses).
Paxéus, 1996	Effluent wastewaters from a large number of automatic vehicle washing facilities in Göteborg (Sweden) have been fully monitored. COD, and oil content have been fully measured. A material balance study did not show full elimination of the organic pollutants in the oil separator, probably due to the formation of difficult to separate stable emulsions.
Nace, 1975	In areas where de-icing salts are used, sodium chloride levels may build-up in the reclaimed water. Samples of car wash reclaimed waters were taken over winter season in two Canadian cities, and analyzed for sodium chloride content. Results showed an average sodium chloride content of 0.039 % at Winnipeg, and 0.023 % at Edmonton. Authors believe that significant corrosion can occur with a concentration of chloride in the water as low as 0.04 % (400 $mg.L^{-1}$).

Rubio and Zaneti (2009) have developed and applied the flocculation column-flotation (FCF) technique for vehicles wash wastewater reclamation in Brazil, and reported a high turbidity and colour removal (> 90 and 75 %, respectively). Main features observed were the low surface tension (as a result of residual surfactant concentration) of the wash wastewater which facilitates the generation of microbubbles (Féris et al., 2001); the presence of oil and grease yielding light flocs, and a fairly low suspended solids concentration.

Herein, a new technique was studied in a full-scale car wash wastewater reclamation system, where the wastewater and reclaimed water were fully characterized. Main objectives were to establish main operating parameters and reclaimed water quality. Results were discussed in terms of the low technology/low cost/controlled risk approach.

4.2. Materials and Methods

4.2.1. Materials

Figure 4.1 shows the car wash wastewater reclamation system, installed in a washrack, in Porto Alegre – South Brazil. To comply with local regulations, a single three stage oil/water separator was employed after car wash pit. Reclaimed water, fresh water and total water usage were monitored using single-jet water meters. In the wash procedure a neutral and an alkali detergents were employed; both with dodecyl benzene sulfonate - $CH_3(CH_2)_{11}C_6H_4SO_3Na$ - as the main surface active agent. FCF (flocculation-column flotation) process is depicted in Figure 4.2.

The reagent employed in the flocculation was Tanfloc SL, a tannin derivative, at a concentration of 80–350 $mg.L^{-1}$. Fang (2007) characterized and evaluated Tanfloc SL as a coagulant/flocculant, and has reported it as tannin based medium-to-high molecular weight polymer, containing 10 % alum. Charge neutralization, polymer bridging, and sweep flocculation are described by this author as the main operating mechanisms. Sodium hypochlorite, containing 4 - 6 % available free chlorine, was utilized as disinfectant.

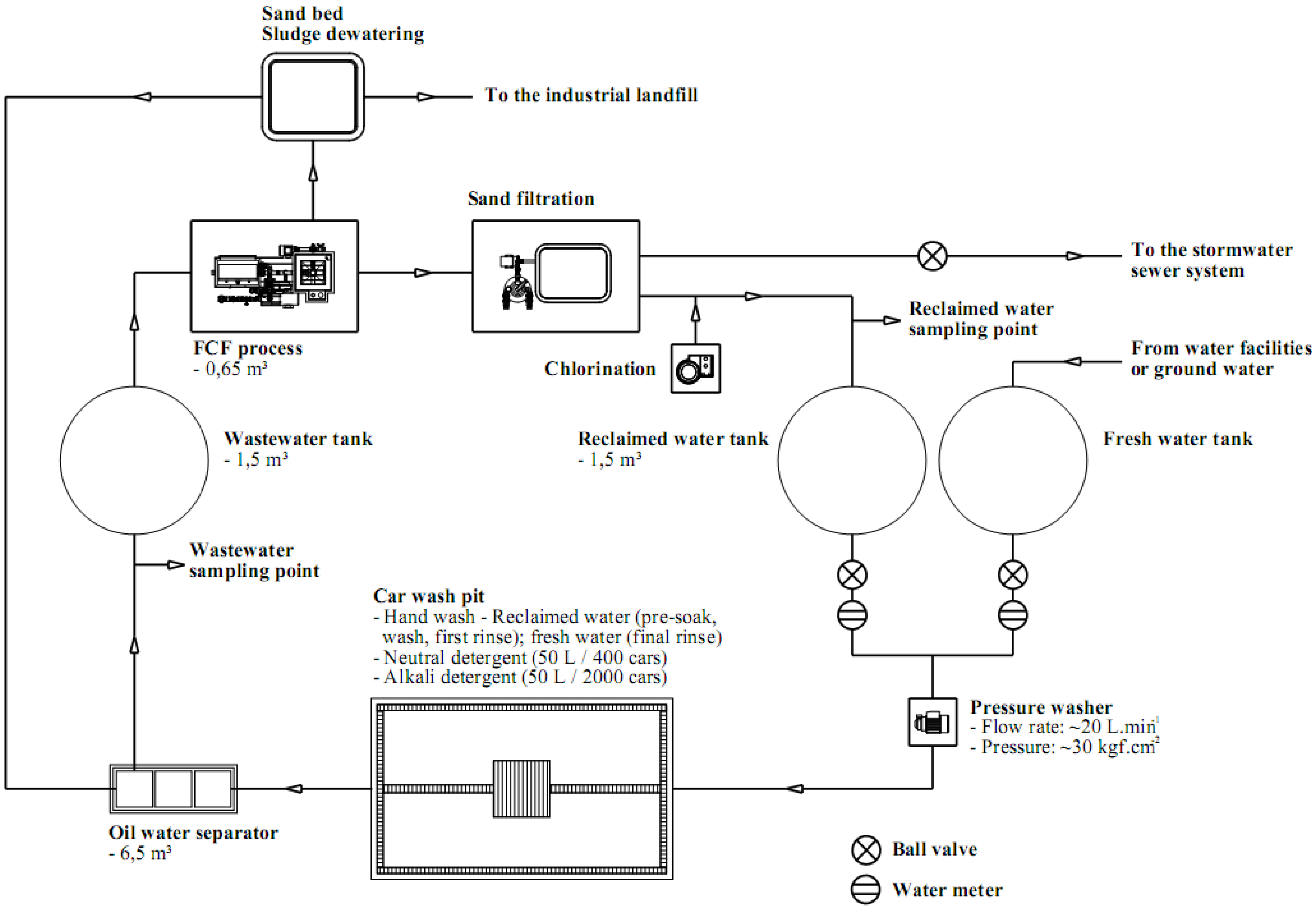

Figure 4.1. Car wash water reclamation system. Total storage capacity - approximately 10 m³.

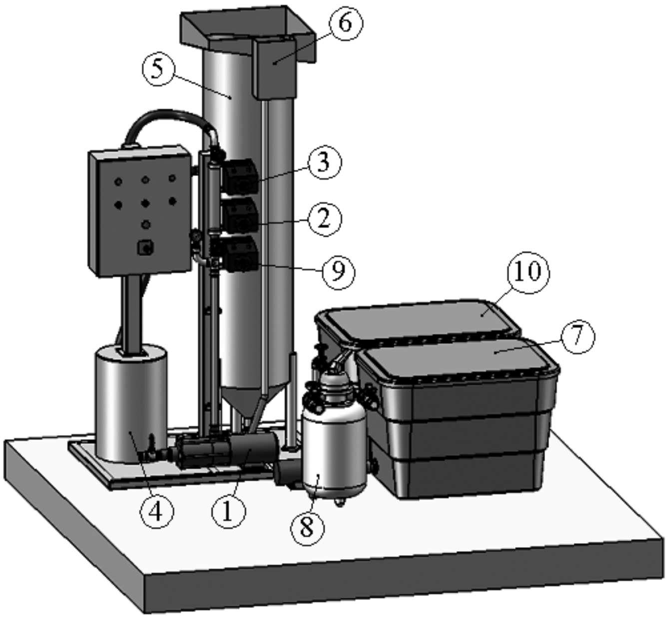

Figure 4.2. FCF car wash wastewater reclamation Rig: 1 - Centrifugal multiphase pump (CMP - bubbles generation unit); 2 – Diaphragm pump (Tanfloc SL dosing); 3 - Diaphragm pump (eventual pH regulator dosing); 4 – Flocculation unit (FGR); 5 – Column flotation; 6 – Column flotation water level control; 7 – Clarified water tank; 8 – Sand bed filter; 9 – Diaphragm pump (sodium hypochlorite dosing); 10 – Sand bed (sludge dewatering).

4.2.2. Methods

Reclaimed water was employed in the pre-soak, wash and first rinse. Fresh water was used in the final rinse, before the cars being dried. The system ran in two rounds (10 hours) per day along 20 weeks. The study was divided in Campaign 1 (6 weeks) and Campaign 2 (14 weeks). Campaign 1 includes results from car wash wastewater treatment by FCF + sand filtration (FCF-S), and Campaign 2, results from FCF+sandfiltration+chlorination (FCF-SC). Sodium hypochlorite was standardized weekly and dosed in low concentration after sand filtration (0.5 $mgCl_2.L^{-1}$). Between Campaign 1 and Campaign 2 (4 weeks gap), the car wash system operated conventionally with no water reclamation. In both Campaigns wastewater treatment process was operated semi-automatically. Water level in the reclaimed water tank was monitored with an electric level sensor; therefore the treatment process was turned-on automatically.

Wastewater and reclaimed water had 21 parameters analysed according to APHA (2005) – see examination methods in Table 4.5. Wastewater samples were collected after oil/water separation, and reclaimed water after chlorination (Figure 4.1). Single and composite (4 aliquots in 2 hours) samples were collected once a week, on mondays mornings. Single samples were analysed by pH, oils and grease, phenol, total and faecal coliforms; and composites by COD; BOD_5; total, dissolved, and suspended solids; chloride; sulphate; sodium; manganese; turbidity; conductivity; hydrogen sulphide; phosphorus; nitrogen; tannin and surfactants.

The build-up of some substances concentrations, as a function of the water cycles, was monitored. One water cycle was considered to occur when the total water volume used in the washes overcomes the storage capacity of the system (10 m³ - Figure 4.1).

According to Montgomery (1991), regression methods are frequently used to analyze data from unplanned experiments, which might arise from observation and uncontrolled phenomena or historical records. Data fitting using linear regression by least squares was applied for processing the results of the wastewater and reclaimed water as a function of time (weeks). Equations employed for linear regression (1) and for coefficient of determination (2) were the following.

$y = b_0 + b_1 x$ (1), where "y" was the observed result (parameter value); "b_0" and "b_1"fitting parameters; and "x" was the independent variable (time).

$\mathrm{R-square} = \frac{S_{xy}^2}{S_{xx}S_{yy}}$ (2), where R-square is the coefficient of determination; S_{xx} and S_{yy}were the standard deviation of "x" and "y" respectively; and $S_{xy}$the covariance.

The following hypotheses were considered:

H_0: R-square < 0.7 - The evaluated water parameter is not dependent on time (water cycles);

H_1: R-square ≥ 0.7 - the evaluated water parameter is considered to be a function of time. In this case, the coefficient (b_1) of the time variable dictates if the data increases ($b_1 > 0$), decreases ($b_1 < 0$), or get stable ($b_1 = 0$).

A cost-benefit analysis of the water reclamation practice for car washes in Brazil was proposed, considering results found in the present study, as water demand, reclamation percentage and wastewater treatment costs (chemicals, energy consumption, fresh water and sludge disposal). Regarding the fresh water supply, it was considered the water costs for commercial activities in two cities in Brazil: Porto Alegre (basic price of U$$ 2.69 – 5.83.m^{-3}) and São Paulo (Table 4.2).

Table 4.2. São Paulo metropolitan region waterprices.

Consumption range	Cost
0 – 10 m³	34.12.U$$.month^{-1}
10 – 20 m³	6.65 U$$.m^{-3}
21- 50 m³	12.77 U$$.m^{-3}
Above 50 m³	13.29 U$$.m^{-3}

The market value for a FCF-SC equipment with a treatment capacity of 500L.h^{-1} is estimated in U$$ 8687.50 (quoted value along with a private company in Brazil).

4.3. Results and Discussion

4.3.1. FCF process

Main equipment design and operating data of the FCF, during both Campaigns, are summarized in Table 4.3. The sludge removed from the column flotation was accumulated in a sand bed and disposed off safely in landfill. The total volume of dry sludge generated during the entire study (20 weeks) was 0.4 m³.

Table 4.3. FCF car wash wastewater reclamation process (1 $m^3.h^{-1}$ flow rate): operating parameters and constructive characteristics.

Bubbles generation unit (CMP)	
Full-flow saturation	Yes
Recycle-flow, %	0
Saturation pressure, atm	20-40
Bubbles diameter range[a], µm	5-250
Bubbles Sauter diameter (D_{32})[a], µm	75
Needle valve, inch	0.5
Flocculation unit (FGR)	
Pipe diameter, m	0.0254
Total length, m	12
Retention time (tr), s	22
Head loss, atmospheres	0.85
Velocity gradient (G), s^{-1}	660
Camp number	14520
Tanfloc SL, $mg.L^{-1}$	80-350
Dosing pump	Diaphragm
Aerated flocs characteristics[b]	
Average diameter, µm	860-1600
Theoretic average strength (σ), $N.m^{-2}$	49-82
Fractal dimension (D_2)	1.64
Rise rate, $m.h^{-1}$	45-165
Flotation unit (column)	
Diameter, m	0.4
Height, m	1.8
Retention time (t), s	814
Hydraulic load, $m.h^{-1}$	8

[a]Measured according to the technique reported by Rodrigues and Rubio (2003).
[b]Measured as in Rubio and Zaneti (2009).

FCF main features are the hydraulic flocculation system employed, the bubbles generator (centrifugal multiphase pumps), the size of the bubbles and flocs and the separating column. The flocculation stage employs an in-line plug flow device – the flocs generator reactor (FGR, Carissimi et al., 2005, 2007), which provides an efficient flocculation at a high velocity gradient (G) at short residence time (Grohmann et al., 1981; Gregory, 1987), therefore reducing the Camp Number (G x tr) and consequently the energy consumption. More, this plug flow flocculator promotes a rapid and efficient floc/bubble contact (Finch, 1995; Rosa et al., 2005; Carissimi and Rubio, 2005), generating the so-called aerated flocs (Oliveira et al., 2010).

With the bubbles being generated by a centrifugal multiphase pump, Lee et al. (2007) reported that they are more cost-effective than the conventionally applied saturator vessels, besides being safer and easy to operate. Rodrigues and Rubio (2003) and Rubio and Zaneti (2009) have measured the bubbles formed by these pumps in the presence of surfactants. Results showed that a similar Sauter mean diameter of 75 μm could be attained, configuring microbubbles (< 100 μm), somewhat higher than those used in conventional DAF operations.

Microbubbles/particles (flocs) main accepted interactions mechanisms are: adhesion through hydrophobic forces; microbubbles nucleation phenomena at solid surfaces; microbubbles entrapment or physical trapping inside the flocs; and aggregates entrainment (Rodrigues and Rubio, 2007; Oliveira et al., 2010). According to the authors, the very rapid rising rate exhibited by these aggregates depends on the number of bubbles attached or entrapped inside the flocs, and this “aeration degree” is a function of the aggregates characteristics (hydrophobicity). The high average rise rate, reported in Table 4.3, is in agreement with those mechanisms, once aerated flocs generated during wash wastewater treatment are exposed to adsorption/co-precipitation of surfactant.

Applications of column flotation are increasing in the environmental area, especially in the treatment of oil and grease (removal from water), metallic ions, de-inking, and suspended solids removal (Finch, 1995; Filippov et al., 2000; Capponi et al., 2006). This device facilitates the prompt rise of the aerated flocs to the top (surface) of the column. Its high hydraulic-load and flux pattern (plug flow) are the main observed advantages. The float layer at the surface of the column consists of a mixture of foam and aerated flocs. This float layer is hydraulic evacuated on top of the column, and flows by gravity towards the sand bed. Clarified water is then removed from the bottom of the column.

Data from Table 4.3 confirms the compactness of the FCF process, operating readily at a hydraulic load of 8 $m.h^{-1}$. Rubio and Zaneti (2009), using a similar rig, reported loadings as high as 15 $m.h^{-1}$, in the treatment of buses wash wastewater, which is much higher than those applied in conventional microbubbles flotation cells (Kiuru, 2001). The explanation for this high hydraulic load relies on the formation of the so-called aerated flocs, which are well structured, very light and highly floatable (Oliveira et al., 2010).

4.3.2. Reclamation system

In the present work, the wash type was a source of conveyor (Brown, 2000), where employees wash the cars using a handheld house with no automatic equipments. Table 4.4 shows results of water usage and saving during both Campaigns 1 and 2. Nearly 2.000 cars were washed, during the 20 weeks of operation, with the mean water volume per car being about 120 L. This consumption is lower than the reported by Ghisi et al (2009) which have considered a water demand of 150 – 250 L per wash when evaluating the potential for potable water savings by using rainwater for car washing in petrol stations in Brasilia, Brazil.

Water usage in car wash relies on wash type. Brown (2002) shows a water consumption difference of more than 500 % when comparing tunnel (268 L per car) and self-service (45 L per car), in Phoenix, U.S.A. These variations in water usage are function of wash equipments and schedule (steps). Al-Odwani et al. (2007), in Kuwait, have reported a water consumption of 185-370 L per car wash when utilizing in-bay wash type. According to Boussu et al. (2006), in Belgium, due to a high capacity of washes, the automatic car washes are the most widespread, and the average water consumption is close to 400 L per wash.

The total used volume of water in Campaign 1 was 7 times the storage capacity (10 m^3 - see Figure 4.1), configuring 7 water cycles. In Campaign 2, total used volume was 15 times the storage capacity (15 water cycles). Results presented in Table 4.4 link the number of water cycles in the system with the elapsed time (weeks).

The percentage of water to be reclaimed was close to 70 % (Table 4.4), and limitation on reclamation seems to be more related to employees training and skills, rather than to the water quality, despite a final rinse with fresh water be imperative. According to Boussu et al. (2006), nearly 15% of the Belgian carwashes already reuses 55% of the wastewater by using different techniques such as sand filtration, adsorption or biological treatment. Brown (2002) reported that 34 % of the professional car washes distributed in Orlando, Phoenix and Boston (U.S.A.), reclaim water. Reclaim ranged from 9 % to 82 % of total water used in the washes and the overall average percentage of recycled water was 51 %.

During the 20 weeks of the study, the wastewater was discarded only once (between the two Campaigns), which along with the water saving compose a substantial environmental gain of this washrack system.

Table 4.4. Water usage and saving as a function of time (weeks).

	Total used water volume, m^3	**Number of water cycles in the system**	**Number of washs**	**Average total volume, L.vehicle^{-1}**	**Average fresh water volume, L.vehicle^{-1}**	**% Reclamation**
Campaign1						
Average and totals	73	7.3	617	119	49	58
Campaign2						
Average and totals	158	15.9	1380	115	38	67

During both Campaigns 1 and 2, the FCF-Sand FCF-SC processes were applied and waste and reclaimed water characteristics were fully monitored (Table 4.5). The process efficiency in removing/reducing total suspended solids (TSS) and turbidity are high for both systems, and no significant difference in reclaimed water clarification was observed. FCF-SC treated water had always turbidity and TSS below 15 NTU and 15 mg.L^{-1}, respectively. Boussu et al. (2006), when monitoring a car wash water reclamation system in Belgian with a hydrocyclone and a sand filter have reported a TSS always higher than 60 mg.L^{-1}. On the other hand, membranes systems are known by their ability in reducing suspended solids and turbidity. Hamada and Miyazaki (2004) employed a flocculation followed by ultrafiltration system to handle 0.05 NTU reclaimed water. Therefore, FCF-SC observed results in car wash wastewater clarification are much higher than some physicochemical proposed systems, and less efficient then sophisticated membrane systems. Flocculation-flotation effectiveness in removing TSS and reducing turbidity is well discussed and reported elsewhere (Bratby and Marais, 1977; Edzwald, 1995; Rubio et al., 2002), and here the formation of aerated flocs was probably facilitated by the mixing characteristics of the plug-flow flocculator (FGR), the polymeric bridges expected to occur when using Tanfloc SL as coagulant/flocculant agent, and the suspended solids surface hydrophobicity (Carissimi and Rubio, 2005).

The oxygen demand values (Table 4.5) of the wastewater in both campaigns were below the local emission limit (COD = 400 $mg.L^{-1}$; BOD_5= 180 $mg.L^{-1}$). These values are lower than those reported by Paxéus (1996) and Panizza and Cerisola (2010), but higher than Hamada and Miyazaki (2004) results. It seems that detergents are the most prominent responsible for oxygen consumption in car wash wastewater (Boussu et al., 2006). In Campaign 1, the BOD_5 concentration showed a dependence on time and build-up (Table 4.5 and Figure 4.3; see its R^2 and fitting parameter - b_1), even with a feed inlet of 40 % of fresh water. Results may be explained by the increase of the BOD_5 dissolved fraction (Odegaard, 2001). Wastewater BOD_5 concentration in Campaign 2 (Table 4.5) did not show build-up. These results can be explained by the oxidation skill of the chlorination process (Metcalf & Eddy, 2006).

Wastewater treatment plants, agricultural runoff and wildlife constitute possible sources of faecal pollution. From most commonly used faecal indicator organisms, faecal coliforms, denote faecal contamination but not whether it is of human or animal origin (Wéry et al., 2010). Some faecal bacteria, such as E. coli and enterococci, survive, grow, and establish populations in natural environments such as fresh water lakes and streams, sand beach, soils and sediments, and plant cavities. Therefore, it is reasonable that car wash wastewater may experience faecal coliforms contamination. Table 4.5 shows that coliforms (total and faecal) counting in wastewater is fairly high, possibly posing some health risk (Metcalf & Eddy, 2006) and showing the need for disinfection. After chlorine was added (FCF-SC), the total and faecal coliforms concentrations were reduced by 95 and 99 % (2 log removal), respectively, diminishing this risk.

Brown (2000; 2002) comments odour problems related to the presence of bacteria in car wash waste and reclaim water. Coliform counting is not performed by this author, or comments on the health risk. Hamada and Miyazaki (2004) have performed E. Coli counting in car wash wastewater and reclaimed water. According to the authors, E. Coli was not detected in these waters, although the results are expressed as <5 $CFU.mL^{-1}$, which may be an inconsistent unit for bacteria counting.

Hydrogen sulphide (H_2S) formation appears to be a result of a microbial process taking place at anaerobic conditions (Hvitved-Jacobsen et al., 2000) and its odour threshold is substantially low – 0.41 $mg.m^{-3}$ (Kim and Park, 2008). Mean concentrations (Table 4.5), measured in wastewater (0.19 $mg.L^{-1}$) and in reclaimed water (0.02 $mg.L^{-1}$), reached to about 88 % removals (chlorine oxidation) (Boon, 1995). This reduction in H_2S was sufficient to eliminate odour problems.

Oil might be present in water as free (> 150 µm), dispersed (150 - 50 µm), emulsified (50 – 0.1 µm), and/or soluble (< 0.1 µm) form. Free and dispersed forms are efficiently removed by gravity in oil/water separator devices. Emulsified fraction consists of stable oil droplets, which have to destabilize before removal (Rosa and Rubio, 2005). Paxéus (1996), when evaluating the wastewater of several automatic vehicles washing facilities in Sweden, has observed an oil concentration range of 10 – 1750 $mg.L^{-1}$ (mean concentration of 291$mg.L^{-1}$). According to the author, oil separator devices have no efficiency in removing this oil, due to the formation of stable emulsions in the wastewater caused by detergents used in the cleaning steps of vehicles. On the other hand, Hamada and Miyazaki (2004) and Al-Odwani et al. (2006) reported low concentrations (lower than 25 $mg.L^{-1}$) of oil in automatic vehicles washing facilities in Japan and Kuwait, respectively. Table 4.5 shows that the oil concentration in wastewater herein was quite low, in average below 10 $mg.L^{-1}$ (emission limit). In this work, wastewater sampling were carryout downstream of the oil separator (Figure 4.1). As this gravity device is known to separate free and/or dispersed oil droplets, it could be stated that the detergents used were not responsible for oil stabilization. Besides, phenol concentration was quite small (0.02 $mgC_6H_5OH.L^{-1}$), much lower than the local limit (0.1 $mgC_6H_5OH.L^{-1}$).

Once dodecyl benzene sulfonate was employed, the presence of residual surfactant in wastewater was expected (Table 4.5): 12 mg.L^{-1} (Campaign 1) and 21 mg.L^{-1}(Campaign 2) surfactant-MBAS (anionic). Those concentrations are much higher than the permitted by the local environmental regulation (2 mg MBAS.L^{-1}). The efficiency of FCF-SC in reducing the surfactant-MBAS (anionic) was about 40 %. Physical carryover by bubbles; adsorption/co-precipitation within the aerated flocs; oxidation by chlorination may be responsible for the surfactant molecule destruction and/or immobilization by adsorption.

Wastewater conductivity dependence on time and build-up were found (Figure 4.4) for wastewater in Campaign 1. In Campaign 2, contrary to expectations, no TDS concentration build-up occurred after flotation and chlorination (Table 4.5). Both parameters, TDS and conductivity, are higher in Campaign 1 than in Campaign 2, as a result of oxidation of the dissolved constituents by chlorination. Conductivity and TDS values are in the range already reported by Panizza and Cerisola (2010) and Hamada and Miyazaki (2004).

Sulphate, chloride and sodium ions concentrations in both, wastewater and reclaimed water (Table 4.5), for Campaign 2 were quite close, within the experimental error (about 5%). Conversely, Al-Odwani et al. (2007) reported higher ions concentrations in car wash wastewater generated in Kuwait, probably due to the use of desalting water, the water source of that country.

Scaling is commonly characterized by the appearance of an adherent mineral surface deposit (spot) usually composed of calcium carbonate - $CaCO_3$ (Ghizellaouni et. al, 2007). In this work, average calcium ions concentrations reached about 14 mg.L^{-1}, yielding almost 35 mg $CaCO_3.L^{-1}$. According to Metcalf & Eddy (2006), scaling occurrence would begin at an equivalent concentration of 100 mg $CaCO_3.L^{-1}$.

Table 4.5. FCF-S and FCF-SC process: Characterization of wastewater and reclaimed water during (mean values ± 1/2 standard deviation).

Parameters	Campaign 1 – FCF-S				Campaign 2 – FCF-SC				Examination Methods
	Wastewater	R^2	Reclaimed water	R^2	Wastewater	R^2	Reclaimed water	R^2	
pH	7.7±0.6	-	7±0.3	-	7.4 ± 0.8	-	7.3 ± 0.5	-	-
BOD_5, mg.L^{-1}	133±61	0.75	-	-	68 ± 13	0.23	27 ± 11.5	0.54	5520 B
COD, mg.L^{-1}	241±23.5	0.46	-	-	191 ± 22	0.00	71 ± 25	0.36	5210 B
TSS, mg.L^{-1}	68±19	0.64	-	-	89 ± 54	0.19	8 ± 6	0.36	2540 D
TDS, mg.L^{-1}	502±90.5	0.44	-	-	345 ± 27.5	0.17	387 ± 47	0.00	-
Conductivity, µS.cm^{-1}	633±125	0.74	684±92	0.66	469 ± 39.5	0.33	572 ± 69	0.01	2520 B
Turbidity, NTU	89±16.5	0.39	12±8	0.26	103 ± 57	0.12	9 ± 4	0.05	2130 B
Total coliforms, CFU.100mL^{-1}	1.80E+06	0.01	-	-	4.7E + 5	0.28	2.1E + 4	0.24	9223 B
Faecal coliforms, CFU.100mL^{-1}	1.35E+03	0.08	-	-	1.7E + 4	0.00	1.2E +2	0.09	9221 E
Tannin, mg.L^{-1}	17±2.5	0.25	-	-	10 ± 2	0.04	6 ± 2	0.26	5550 B
Oil and Grease, mg.L^{-1}	6±1	0.28	-	-	11 ± 11	0.00	8 ± 4	0.06	5520 B
Phenol, mg.L^{-1}	0.02±0.01	0.22	-	-	0.01 ± 0.01	0.19	0.01 ± 0.01	0.00	5530 C
Surfactant, mg.L^{-1}	11.7±9	0.25	-	-	21 ± 3.6	0.06	12 ± 2.3	0.07	5540 C
Phosphorus, mg.L^{-1}	1±0.5	0.19	-	-	1 ± 1	0.00	0.5 ± 0.4	0.03	4500 P A
Nitrogen, mg.L^{-1}	5±1	0.33	-	-	9 ± 3	0.13	8 ± 2	0.41	4500 NH_3 C
Hydrogen sulphide, mg.L^{-1}	-	-	-	-	0.19 ± 0.01	0.00	0.02	0.07	4500 D
Calcium, mg.L^{-1}	-	-	-	-	16 ± 2	0.5	14 ± 3	0.03	
Magnesium, mg.L^{-1}	-	-	-	-	2.2 ± 1	0.00	1.4 ± 1	0.03	Ion cromatography
Sodium, mg.L^{-1}	-	-	-	-	76.7 ± 11.5	0.32	90.8 ± 14.5	0.19	
Sulphate, mg.L^{-1}	-	-		-	22.6 ± 2.5	0.66	23.8 ± 2.5	0.63	4110 B
Chloride, mg.L^{-1}	-	-	-	-	30.9 ± 4.5	0.52	59.3 ± 14.5	0.03	

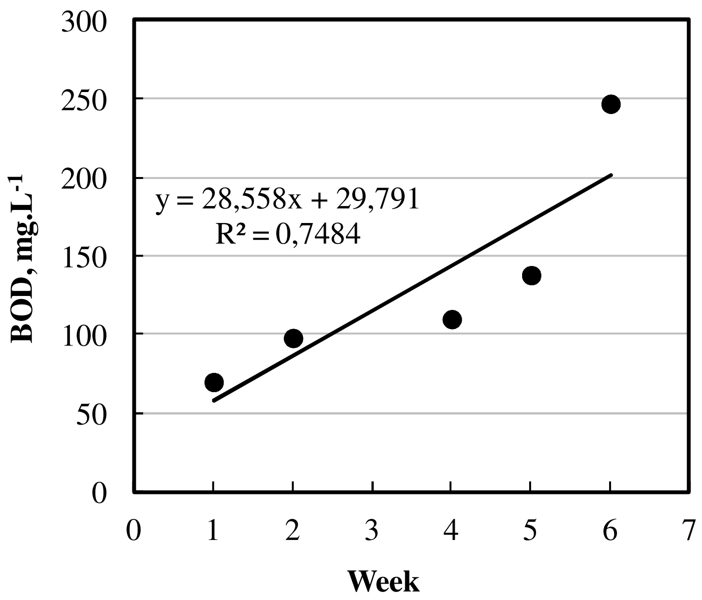

Figure 4.3. FCF-S process: wastewater BOD_5 as a function of time.

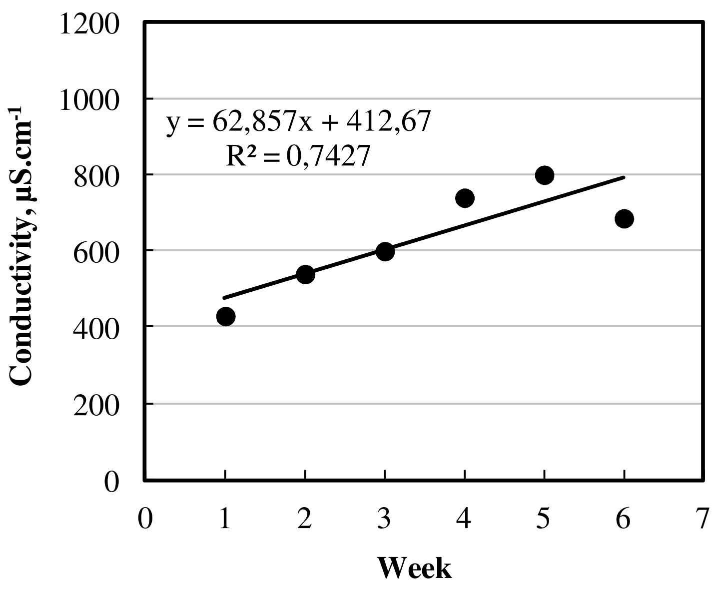

Figure 4.4. FCF-S process: wastewater conductivity as a function of time.

The economic evaluation (approximate values) considered hypothetical data based on the present study (120 $L.car^{-1}$, 70 % of reclamation, car wash wastewater treatment cost of U$$ 0.40.m^{-3}, FCF-SC equipment cost of U$$ 8,687.50).

Economy and FCF-SC equipment amortization as a function of average daily washes is shown in Figure 4.5. Considering a car wash wastewater reclamation system in Porto Alegre, with 35 daily washes, the equipment amortization is achieved in 24 months. In São Paulo, due to the higher water prices, a demand of 10 washes per day is sufficient to amortize the equipment in the same period of time. More, in São Paulo-Brazil, when the daily demand reaches 33 washes, less than 10 months are necessary to amortize the equipment investment. Ghisi et al. (2009) have considered a range of 15-45 daily washes when evaluating the potential for potable water savings in car washes in Brasília (BR).

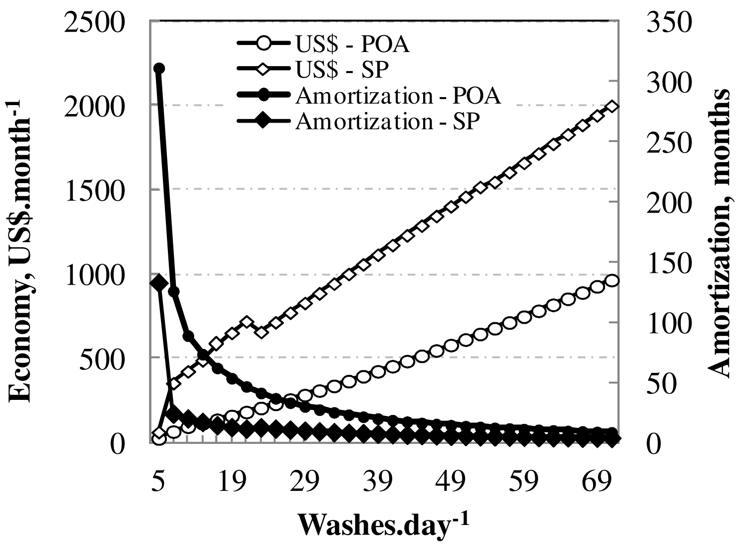

Figure 4.5. FCF-SC car wash reclamation system – economic evaluation as a function of daily washes.

4.4. Conclusions

A full-scale car wash wastewater treatment by FCF – flocculation-column flotation and water reclamation was monitored during 20 weeks of operation. Chemical, physical, physico chemical and biological parameters were measured thoroughly. Noticeable, car wash wastewater and treated (for reclamation) water showed high faecal and total coliforms counting, concluding that no direct reclamation of this water is appropriate without disinfection. Using FCF, sand filtration and chlorination, almost 70 % of odourless and clear water was reclaimed. More than 2000 cars were washed during the 20 weeks and no problems regarding the wash service quality were reported. It is believed that results found may assist a future car wash wastewater safe reclamation regulation, at least, in Brazil.

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MORE ENVIRONMENTALLY FRIENDLY CAR WASHES: WATER RECLAMATION

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5. MORE ENVIRONMENTALLY FRIENDLY CAR WASHES: WATER RECLAMATION

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Abstract

The weight of vehicle wash activities in urban water management is evaluated in Brazil. The treatment of wash wastewater from a typical car wash station by flocculation-column flotation plus sand filtration and chlorination has been fully studied, and reclaimed water criteria are discussed. A quantitative microbial risk assessment (QMRA) was performed with a dose-response model, and an *E.coli* limit of 200 UFC.100 mL^{-1} in the reclaimed water was suggested as acceptable microbiological risk. A mass balance was applied for the assessment of the concentration of critical constituents as a function of water cycles, and the results revealed that the chloride and TDS concentrations in reclaimed water stabilised below 350 and 900 $mg.L^{-1}$, respectively. The cost-benefit analysis performed for six different Brazilian scenarios showed that water reclamation is highly competitive and that the payback period might be as short as one year, depending on water prices and daily wash demand. It is believed that the implementation of the present technology in Brazil and elsewhere is dependent mainly on state policies such as those pertaining to the involvement of larger players (for example, large Brazilian petro station companies) and creating and supporting an early niche market.

Key words: Cleaner production; water reclamation; risk assessment; flocculation-flotation; column flotation; car wash

5.1. Introduction

Water reclamation is the treatment or processing of wastewater to make it reusable by meeting water quality criteria. Water reuse is a promising option for water efficiency in urban areas where black water (sewage or all in-building wastewater streams, including toilet waste), grey water (all in-building wastewater streams, excluding toilet waste), wash water and rainwater are consistently generated (USEPA, 2004).

According to Partzsch (2009), decentralised water reuse schemes are considered to be “more green’’ or ‘‘eco-friendly’’, as they allow water to be treated and processed in a more nature-oriented way. These technologies range from individual homes or clusters of homes to institutional or commercial facilities and are becoming increasingly popular, aided by innovation in reclamation technologies that create high-quality effluent in small-footprint areas.

Vehicle washing is a highly water-consuming process and involves the use of chemicals, generating wastewater with a high concentration of surfactants, oils, greases, waxes and other contaminants, which make these effluents toxic to aquatic life (Brasino and Dengler, 2007). Increasingly restrictive legislation and rising water prices are pushing the car wash industry to invest in process-integrated solutions (recycling - Zotter, 2004; Dunn and Bush, 2001), mainly in Europe, Australia and the U.S., where this activity is one of the primary commercial uses of reclaimed water (Metcalf & Eddy, 2006).

In the current study, decentralised (on-site) water reclamation of vehicle wash wastewater is presented as a means of making the practice “eco-friendly”. A theoretical and an empirical framework are provided to help understand the vehicle wash wastewater issue within a low-technology/low-cost/controlled-risk approach (Anderson et al., 2001), specifically for the implementation of a new technology (flocculation-column flotation - FCF) in Brazil. The objectives of this study were to estimate urban water efficiency, to assess reclaimed water criteria, to perform an economic analysis and to evaluate the innovation chain.

5.1.1. Vehicles-wash water reclamation

According to Brown (2000), the design of a vehicle wash water reclamation system includes the choice of washing chemicals (neutral, alkaline, acid cleaners, detergents and waxes, described by Páxeus, 1996, and Boussu et al., 2007), the implementation of wastewater treatment processes and the intended use of the reclaimed water (step of the wash procedure). Reclaimed water can be used in all stages of the washing process, except the final rinse, where the application of fresh or spot-free water (water treated with Reverse Osmosis) is recommended (Metcalf & Eddy, 2006; Brown, 2000).

Table 5.1 presents scientific articles published on the subject of vehicle wash water reclamation. The most studied technologies are membranes – ultra- and nanofiltration – integrated with pre-treatment. Although these technologies are extremely efficient, the associated costs (implementation, operation and maintenance) are very high, mainly in the third world, where membranes are not fabricated.

Why not use rainwater harvesting systems for vehicle washes? Ghisi et al. (2009) have evaluated the potential of such a system in Brazil. The results show that even with high rooftop areas (greater than 350 m²), water savings are low (32.7% on average) and decrease sharply with increasing water demands. Other disadvantages of this system are high effluent emission and long amortisation periods (Domènech and Saurí, 2011).

Although biological treatments are widely applied for the treatment of domestic sewage in municipal wastewater treatment plants (WWTPs), such technologies do not seem to be attractive for vehicle wash water reclamation, even when using rotating biological reactors (RBC – Jefferson et al., 2004; Cortez et al., 2008). This is due to the following drawbacks characteristics of car wash wastewater: low biodegradability and bad nutrient balance; systems implementation (high investment costs, high footprint area, and slow start-up) and microorganisms' sensitivity to chemicals and temperature variations. Nevertheless, recent advances in biotechnology and the development of technologies and commercial equipment (Hydro, 2009) can make these processes more applicable in the near future (Brown, 2000).

In the vehicle wash industry, a common-sense approach for water reclamation systems is physical-chemical treatment, i.e., flocculation-sedimentation, and direct filtration. Brown (2000) reported that flocculation-sedimentation processes are employed when intending to remove very fine suspended solids and colour, achieving clarified reclaimed water.

As an alternative to flocculation-settling, Rubio et al. (2002) reviewed flocculation-flotation techniques and their applications, and Rubio et al. (2007) demonstrated the application of flocculation-flotation in vehicle wash water reclamation. The following advantages were claimed: low maintenance and operational costs (low reagents costs and a single part-time, unskilled operator required) in addition to moderate investment costs; reduced footprint area and high water clarification. According to the authors, up to 2007, the process has recycled up to 400,000 m^3 of water in more than 20 commercial units operating in Brazil, most of those implemented in bus companies, in the metropolitan area of Porto Alegre - Brazil.

The first generation of the flocculation-flotation equipment consisted of flocculation in two stages (an in-line hydraulic flocculator (FF) for rapid mixing and an agitated tank for slow mixing) followed by conventional dissolved-air flotation. By 2009, Rubio and Zaneti had developed the second generation of the equipment, named flocculation column-flotation (FCF). The main advantages of this technology are (i) the elimination of stirred tanks at the flocculation stage, saving energy and maintenance; (ii) the use of a multiphase pump, which makes the microbubble-generation unit safer and easier to operate when compared to broadly used saturator vessels and (iii) greater compactness (hydraulic load up to 18 $m^3.m^{-2}.h^{-1}$).

Table 5.1. Framework of vehicle wash wastewater treatment and reclamation research.

Technology employed/Reference	Main features	Main conclusions
FCF (Zaneti et al., 2011)	• Full-scale in a commercial car wash • Water audit • Low water chlorination (0.5 $mg.L^{-1}$) • More than 2,000 cars washed with reclaimed water	• Car wash wastewater showed high faecal and total coliforms counting, indicating that no direct reclamation of this water is appropriate without proper disinfection. • The concentration of anionic surfactants in car wash wastewater (21 $mgMBAS.L^{-1}$ in average) is much higher than that permitted by the local environmental regulation (2 mg $MBAS.L^{-1}$). The efficiency of FCF in reducing the surfactant-MBAS (anionic) was approximately 40%. • Using FCF, sand filtration and chlorination, almost 70% of odourless and clear water was reclaimed
Almeida et al. (2010)	• The study compares, by environmental accounting in emergy three bus washing systems operating in São Paulo. Two of these companies use the conventional washing system, using water from artesian wells and disposing the effluent in the public network or in water bodies. The third company uses a rainwater harvesting system together with a treatment plant for water reuse.	• A comparison of the environmental cost of the wastewater treatments showed that the best environmental option is the installation of a wastewater treatment plant within the companies for decentralised water reuse.
Electrochemical oxidation (Panizza and Cerisola, 2010)	• Bench-scale study • Treatment of real car wash wastewater	• Removal of 75% of COD with 0.14 $kWhm^{-3}$ of energy consumption
Rainwater harvesting (Ghisi et al., 2009)	• Computational analysis of the potential for potable water savings in petrol stations located in Brasília, Brazil • Investment feasibility analysis	• It was observed that the average potential for potable water savings by using rainwater is 32.7%, but it can vary from only 9.2% to 57.2%. • If the water utility is to charge for the sewage due to rainwater use, paybacks will be at least 8 years
FCF (Rubio and Zaneti, 2009)	• Pilot study • Treatment of a real bus wash-rack wastewater • Evaluation of a technique for flocculation (FCF) for the	• High hydraulic load capacity (> 15 $m.h^{-1}$) of the system • Turbidity lower than 9 NTU and colour reduction greater than 60%.

	treatment of vehicle (bus) wash-rack wastewater and water reuse	• High potential for water reclamation
Flocculation-flotation (Rubio et al., 2007)	• Theoretical presentation of the flocculation-flotation process, focusing on in-line flocculation and dissolved-air flotation - FAD • Disclosure and report of development and commercialisation of the flocculation-flotation process in vehicle wash wastewater treatment for reuse	• Advantages of the flocculation-flotation process are high hydraulic load (up to 9 $m.h^{-1}$), and water clarification (at least 85% turbidity reduction) • Up until 2007, the process has recycled up to 400,000 m^3 of water in more than 20 units operating in Brazil
Separation/settling tank, oil/water separator, multimedia filter (which contains layers of gravel, green sand, and carbon), and a 5 micron cartridge filter (Al-Odwani et al., 2007)	• Prototype car wash reclamation system • Full-scale application	• 75% of the water used in the car wash stations could be reused • An average consumption of approximately 25% of fresh water is needed as feed to perform final rinses and make-ups
Nanofiltration membranes (Boussu et al., 2007)	• Bench-scale study • Wastewater from an automatic car wash • The study describes specific legislation in Europe	• Best results with a hydrophilic membrane (applied pressure-8 atm; temperature held at 293 K) • Need to clean the membranes after filtration • Surfactants and other organics removal efficiency up to 95%
Ultrafiltration membrane with the aid of flocculation and activated carbon treatments (Hamada and Miyazaki, 2004)	• Full-scale	• Values of BOD and COD in the reused water ranged from 2.5 to 14.0 mg/L and 4 to 16 mg/L, respectively • pH value, concentrations of Na^+, Cl^-, SO_4^{3-}, electric conductivity and calcium hardness in these waters were similar to those in drinking water • *E. coli* was not present in the car wash wastewater or in the reuse water
Brown (2002)	• Monitoring of 31 commercial car washes in the United States (Boston, Phoenix, and Orlando) • Water consumption and loses by evaporation and carryout are determined	• Water consumption per wash varies from 130 L (conveyor wash) to 175 L (in-bay wash) • Water losses by evaporation and carryout are higher in in-bay washing (30%) than in conveyor washing (16%)

		• Eleven of the 31 sites studied had some form of reclamation system. Water-reclamation percentage ranged from 9 to 80%, and a higher percentage was observed where more sophisticated process were applied
Ultrafiltration membranes (Jönsson and Jönsson, 1995)	• Bench-scale study • The membrane performance when treating wastewater collected at a car wash at different times of the year was studied	• The flux and COD retention when treating the wastewater from the car wash were 30-50 $L.m^{-2}.h^{-1}$ and 60%, respectively

Recently, Zaneti et al. (2011) validated the FCF technique in a full-scale commercial by-hand car wash reclamation system, where almost 70% of odourless and clear water was reclaimed over a period of 22 weeks in a system with virtually no wastewater emission. Figure 5.1 illustrates typical reclamation systems employing the FCF process in car and bus washes for by-hand and automatic washing schemes. In the automatic scheme, water savings reach up to 80%. An activated-carbon filtration system may be employed when emission (purge) is accomplished, increasing surfactant removal before emission, to comply with environmental regulations.

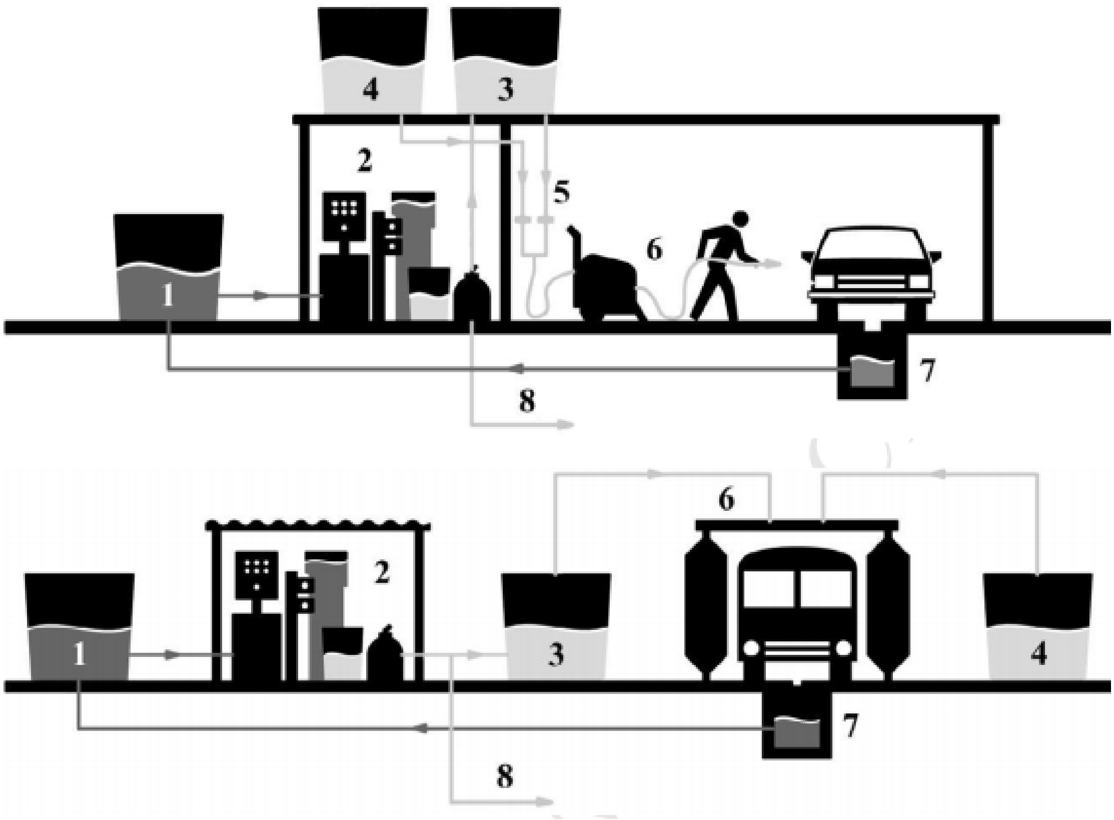


Figure 5.1. Typical reclamation systems employing FCF in car and bus washes. 1. Wastewater tank; 2. FCF equipment; 3. Reclaimed water tank; 4. fresh-water tank; 5. Dual piping for washing machine (hand wash only); 6. Washing machine – By-hand or Automatic; 7. oil/water separator and 8. Purge.

5.1.2. Reclaimed water criteria in vehicle wash

Guidelines from the WHO and USEPA (2004) are far too stringent, and there is a need for less conservative standards (*fit for purpose* – Metcalf & Eddy, 2006). Water criteria for vehicle wash reclamation systems must include public acceptance, aesthetic quality, microbiological risk and chemical issues. Jefferson et al. (2004) and Friedler et al. (2006) researched public acceptability in England and Israel, respectively, of water reuse in urban modalities. For vehicle wash operations, wide acceptance has been reported for the strict control of aesthetic (odourless, and low turbidity) and microbiological (low health risk) quality.

Brown's reports (2000; 2002) for the International Carwash Association corroborated the results of these studies, indicating that the water quality for vehicle washes must be sufficiently high such that vehicles and wash equipment are not damaged (corrosion, scaling, and spots - chemical risk), the risk to operators and users is minimal (microbial risk), and the aesthetic conditions are acceptable.

The microbiological risk, which is a major concern, has not yet been measured. This risk may be estimated by quantitative microbial risk assessment (QMRA), defined as the application of the principles of risk assessment to estimate the consequences of a planned or actual exposure to infectious microorganisms (Hass et al., 1999). QMRA has been applied to establish standards, guidelines and other recommendations regarding drinking water and water reuse (FDEP, 1998; Huertas et al., 2008) and can be performed using dose-response models.

The addition of chemicals in wastewater treatment, including chlorine to disinfect reclaimed water, increases the salt concentration, and this may build up to the point where the reclaimed water becomes unsuitable for reuse (Metcalf & Eddy, 2006; Zaneti et al., 2011). This chemical risk (scaling, spot formation and corrosion) may be predicted and monitored by the application of a mass balance (Morelli, 2005), utilising SDT and chloride as control parameters.

5.1.3. Policies for decentralised water technologies

In the USA (San Antonio – TX, Denver – CO and Seattle – WA) and Canada (Toronto), there are certification and water rebate programs regarding decentralised water technologies. Vehicle wash operators must comply with conservation techniques (water saving equipment, spray nozzle replacement, prompt repair of leaks, water reclamation) and may receive rebates of up to 50% of the implementation costs, reducing payback periods to five years or less. Other advantages of these incentives are technical support, protection from shutdown during advanced droughts and signs identifying the car wash operator as a recognised water saving partner.

The Queensland (Australia) Water Commission has elaborated water efficiency guidelines for commercial washers, including large vehicles and fixed commercial premises. The implementation of measures or actions to use water efficiently within the business are assessed, identified, assisted and certified by a water efficiency expert. Large-vehicle (buses, trains, aircraft, trucks, trailers and military vehicles) washes must be established with high-pressure water-cleaning units operating at a flow rate up to 20 litres per minute and with a maximum volume of 100 litres of fresh water per vehicle. To achieve this efficiency, alternative water sources (rain or reclaimed) should be used. Fixed commercial premises must use, at most, 70 L of fresh water in a standard vehicle wash. Compliance must be demonstrated by keeping a weekly written record of the number of vehicles washed and the amount of water used. An operator's failure to comply with any or all of the criteria within these guidelines will result in his or her business not being able to operate anymore.

In some European countries, water recycling in car washes is already legislated. In Germany and Austria, a minimal recycling percentage of 80% is imposed, while in the Netherlands and in the Scandinavian countries, a maximum fresh water consumption rate of 60–70 litres per car is enforced. In Belgium, a recycling percentage of 70% will be needed in the future to obtain an environmental license (Boussu et al., 2007).

In Brazil, a national regulation (CNRH, 2005) encourages and provides general criteria for non-potable water reuse. Because vehicle washes are among the modalities for water reuse, the Federal District drafted a regulation obligating car wash wastewater reclamation in petrol stations. Nevertheless, due to the lack of local technical and political support, the law is now (six years after its passing) unenforced; thus, vehicle-wash water reclamation is not commonly applied in this region.

In Curitiba and Porto Alegre, it is mandatory to install rainwater harvesting systems in new buildings with rooftops spanning across more than 500 m². Regarding vehicle wash activities, there are no water efficiency regulations yet, and the only environmental requirement enforced by law is the use of oil/water separator devices as the wastewater treatment step before the emission of the effluent to the storm-water network. Nonetheless, as will be presented later, the drivers for water reclamation in Brazil are water and wastewater prices (varying from US$ 3.5 to more than US$ 13 per cubic meter).

As described above, international policies regarding water consumption during vehicle washing vary between certification programs, water saving rebates and regulations. These policies are conducted by water operators, water agencies, municipalities and car wash associations and help move decentralised technologies along the innovation chain. In Germany, for instance, there are basically three state policy instruments that support the implementation of rainwater harvesting and eco-buildings: investment grants, water extraction fees and separate water and wastewater fees (Partzsch, 2009). However, some gaps can persist in the commercial maturity of these “eco-friendly” technologies.

Foxon et al. (2005) defined the stages for the innovation chain of a technology as basic and applied R&D, demonstration, pre-commercial, supported commercial and commercial. According to the authors, the most frequent innovation difficulties and failures occur at the transition between the demonstration stage and the pre-commercialisation stage, as well as at the transition between the pre-commercialisation and supported commercial stages.

5.2. Materials and Methods

5.2.1. Urban water efficiency

Urban water efficiency (UWE) refers to water savings (quantitative) and wastewater minimisation (qualitative gains) with respect to the overall urban pattern (Domènec et al., 2011; Villarreal and Dixon, 2005). The potential for vehicle washes to increase UWE in some Brazilian state capitals - São Paulo, Curitiba, Brasília, Recife, Salvador and Porto Alegre were estimated, considering the implementation of water reclamation systems for car (70% reclamation rate and 5% wastewater return flow), bus and truck washes (80% reclamation rate and 5% wastewater return flow). The design parameters utilised for the theoretical UWE calculations are presented in Table 5.2 and Table **5.3**.

To estimate urban water demand, the latest demographic data were considered. For vehicle wash demand in the commercial sector, the 2012 Brazilian national fleet and a frequency of 3 washes per year for cars, once a month for trucks and twice a month for buses were fixed. These assumptions are considered conservative, as Villarreal and Dixon (2005) have reported a frequency of once a month for car washes in an urban area of Sweden and Almeida et al. (2010) have reported that buses from transport companies in the metropolitan area of São Paulo are washed at the end of each day.

For urban and vehicle wash wastewater characteristics, data presented elsewhere were utilised – see Table 5.2. These characteristics are strongly variable; Páxeus (1996) and Huang et al. (1984), for example, have presented COD values of over 3,000 $mg.L^{-1}$ for heavy-vehicle wash wastewater, while Boussu et al. (2007) have reported a surfactant concentration of up to 56 $mg.L^{-1}$ in a car wash. The characteristics of vehicle wash wastewater that are considered in the present study are those observed after treatment in an oil/water separator - the employment of this treatment device in Brazil is enforced by law.

Table 5.2. Characteristics of urban and vehicle wash wastewater.

	Volume	COD, $mgO_3.L^{-1}$	Surfactants, $mg.L^{-1}$	Total phosphorus, $mgP.L^{-1}$	Total nitrogen, $mgN.L^{-1}$	Reference
Urban wastewater, $L.inh^{-1}.day^{-1}$	200	430	4	7	40	Metcalf & Eddy (2006)
Car-wash wastewater, $L^3.wash^{-1}$	130	191	21	1	9	Zaneti et al. (2011)
Bus-wash wastewater, $L^3.wash^{-1}$	350	307	6.3	8.5	5	Rubio and Zaneti (2009) and unpublished data
Truck-wash wastewater, $L^3.wash^{-1}$	350	600	21	8.5	30	Unpublished data

Table 5.3. Data on the Brazilian population and its national fleet of vehicles.

	Population, inhabitants	Car fleet, unit.	Bus fleet, unit.	Truck fleet, unit.
São Paulo	10,931,749	5,059,970	73,196	390,957
Salvador	2,593,768	514,672	11,079	47,431
Brasilia	2,499,942	1,033,896	13,420	88,790
Curitiba	1,716,924	981,564	11,332	94,155
Recife	1,488,689	366,552	6,033	32,864
Porto Alegre	1,391,434	565,897	6,867	36,482

5.2.2. Full-scale studies

The car wash (by-hand scheme) wastewater reclamation system (Figure 5.1) installed in Porto Alegre, South Brazil was monitored over a period of 20 weeks. Neutral and alkali detergents (both containing dodecyl benzene sulphonate - $CH_3(CH_2)_{11}C_6H_4SO_3Na$ - as the main surface-active agent) were employed in the wash procedure. Reclaimed water was utilised in the pre-soak, wash and first rinse (wash process), and makeup (fresh – tap water) water was used in the final rinse before the cars were dried. Water usage was monitored daily by single-jet water meters. A single three-stage oil/water separator was employed after the car wash rack to remove excess oil content (free oil) and grit particles.

The wastewater treatment process (FCF) ran semi-automatically. The reagents employed were Tanfloc SL (a tannin derivative, optimised by using concentration of 80–350 mg.L^{-1}), during the coagulation step, and sodium hypochlorite (standardised weekly - 0.5 mgCl_2.L^{-1}), during the chlorination step. The chemical, physicochemical and microbiological parameters of the wastewater and reclaimed water were analysed (APHA, 2005) using samples that were collected after oil/water separation and after chlorination.

5.2.3. Microorganism inactivation - bench-scale studies

Aliquots of 500 mL of reclaimed water (see sampling point in Figure 1) were chlorinated (initial concentrations of 5 – 40 mgCl_2.L^{-1}) in glass beakers and gently mixed over different contact periods (30 – 240 min). Following chlorination, sodium thiosulphate was added to neutralise the action of chlorine (Winward et al., 2008). Neutralised samples were stored at 4 ± 1° C for a maximum of 24 hours prior to *E. coli* enumeration.

5.2.4. Coagulation-flocculation + chlorination - bench-scale studies

Jar tests were performed with real wastewater samples (collected after the oil/water separator) to determine the optimum clarification conditions for two types of coagulants: polyaluminium chloride - PAC (followed by a 5 mg.L^{-1} dosage of cationic polyacrylamide – Flonex 9045) and tannin (Tanfloc SL). A volume of 100 mL of supernatant (clarified) liquid was pipetted into a glass sampling beaker and chlorinated with an initial dose of 15 mgCl_2.L^{-1}. Chlorinated samples (duplicate) were analysed to determine TDS and chloride (APHA, 2005).

5.2.5. Microbiological and chemical risks studies

Regli et al. (1991) determined the parameters for the exponential and beta-Poisson models for different microorganisms. During vehicle wash activities, the individuals who may be at risk are the users (customers) and operators. The exposure routes (pathways) to be considered are aerosol (for all individuals, in all washing schemes), and ingestion (operators in by-hand washing schemes). Because toilet flushing, washing faecally contaminated laundry, childcare, and showering are not included in these wastewater streams, the faecal load (Ottoson, 2003; Ottoson and Stenström, 2003) seems to be negligible and the use of *E. coli* for QMRA is appropriate. The infection model for *E. coli* is shown in Table 5.4. The ingestion doses for vehicle wash activities are considered to be the same as those for irrigation activities. Ottoson (2003) utilised a spray nozzle water-drop size distribution (in average 0.5 mm – 50 µl.drop^{-1}, or less (Kincad et al., 1996)) to determine these doses.

Table 5.4. Microbiological risk calculation: Model and parameters.

Organism	**Model**[a]	**Parameters**
E. coli	$P_1^{*}=1-(1+N/\beta)^{-\alpha}$ (Beta-Poisson)	α=0.1705 $\beta=1.61\times10^{6}$ N – Exposure, as number of organisms ingested
Activity	**Exposure route**	**Dose**[s] **(mL)**
Car wash	Aerosol	T^{**}(0,01;0,1;0,5)
Car wash	Ingestion (routine exposure)	T(0,1;1;2)
Extrapolation of daily risk[c]		
$P_n^{***}=1-(1-P_1)^n \approx n \times P_1$		Simplification valid for $P_1<<1$

[a](Huertas et al, 2008);
[b](Ashbolt et al., 2005);
[c](Hunter et al., 2003);
*Probability of infection after a single exposure;
**Triangular distribution (minimum; mode; maximum);
***Probability of infection after a repeated (n times) exposures.

The chemical risk was evaluated by the employment of a mass-balance model (Equations 1, 2 and 3). The evaluated parameters were TDS and chloride, as they may be responsible for corrosion and/or scaling (Metcalf & Eddy, 2006). The following hypotheses were considered:

a) The mass value added during the car wash and wastewater treatment process is constant (Equation 2), in each water cycle, and there is no water loss (Equation 3);
b) One water cycle is considered to occur when the total water volume used in the washes reaches the storage capacity of the system (10 m³ in the full-scale study).

$$C_{R+i} = \frac{CS + (F.V_{Li}.C_{ri} + (1-F).V_{Li}.C_N)}{V_{Li}} \qquad \text{Equation (1)}$$

$$CS = V_{Li}.(C_1 - C_N)$$ Equation (2)

$$V_{Ei} = V_{Li} = F.V_{Ri} + (1 - F).V_{Ni}$$ Equation (3)

Where,

C_{Ri} and C_{Ri+1} = the TDS or Cl^- concentration in reclaimed water during cycle Ri and Ri+1, i = 1,.., n;

CS = Mass of the quality parameter added during the car washing/water-treatment processes;

F = Recycling ratio (0 – 1);

V_{Li} = Total volume of water used in the car wash;

V_{Ei} = Wastewater volume;

V_{Ni} (L) = Fresh water volume;

C_N = TDS or Cl^- concentration in fresh water.

The bench-scale (jar tests) and full-scale results were utilised in the mass balance equations.

5.2.6. Cost-benefit analysis in Brazil

The cost estimation and assessment for the FCF equipment needed for vehicle wash reclamation systems are based on a market survey performed by Zaneti et al. (2011). According to these authors, the market value for a FCF system (1.000 $L.h^{-1}$ capacities) in Brazil is US$ 8,687.50. The cost-benefit analysis of the water reclamation practice for vehicle washes in Brazil was conducted based on the cost of FCF equipment in addition to the operation and maintenance costs of the treatment process (calculated in the present study for chemicals, makeup water, energy consumption, and sludge disposal). Manpower was not considered in the calculation due to the simplicity of the operation of the FCF process (operated semi-automatically by the car wash team). The amortisation (payback time) was calculated as the ratio of the cost of FCF equipment to the economy (monthly savings afforded by implementing the system) - Equations 4 and 5.

a = c/e Equation 4

e = x – (y+z) Equation 5

Where

A = Amortisation (months);

c = FCF equipment cost (US$);

e = Economy (US$.month^{-1});

x = monthly cost of water with no water recycling (US$.month^{-1});

y = monthly cost of FCF process with 70% (cars) and 80% (buses reclamation rate (US$.month^{-1});

z = monthly cost of makeup (fresh) - 70% (cars) and 80% (buses) reclamation rate (US$.month^{-1}).

Fresh-water prices vary amongst the different cities in Brazil; therefore, the amortisation was calculated for 5 different state capitals – São Paulo, Curitiba, Brasília, Recife, Salvador and Porto Alegre – considering 15-70 cars and 10-45 buses washed per day.

The water prices in the cities of São Paulo, Curitiba, Brasília, Recife, Salvador and Porto Alegre are shown in Table 5.5 and the FCF maintenance and operation costs in table Table 5.6.

Table 5.5. Water* costs in Brazil.

Number of daily washes	Water consumption (m³.month^{-1})**	Water costs (US$.m^{-3})					
		São Paulo	Curitiba	Brasília	Recife	Porto Alegre	Salvador
Cars - 15	46.8	12.76	4.33	8.15	8.94	3.58	11.18
Cars - 45	140.4	13.29	4.40	8.65	8.94	5.00	13.18
Cars - 70	221.52	13.29	4.42	8.74	8.94	5.83	13.18
Buses or trucks – 10	120	13.29	4.38	8.51	8.94	4.36	13.18
Buses or trucks – 30	240	13.29	4.42	8.77	8.94	6.26	13.18
Buses or trucks – 45	360	13.29	4.43	8.81	8.94	7.23	13.18

*Wastewater collection and treatment costs are included.
**Considering 26 days of operation per month, 130 L per car, and 350 L per bus or truck.

Table 5.6. FCF maintenance and operation costs.

Item	Cars US$.m^{-3}	Buses US$.m^{-3}
Chemicals	0.43	0.86
Sludge disposal	0.07	0.14
Energetic consumption	0.42	0.42
Total	0.80	1.42

5.3. Results and Discussion

5.3.1. Urban water efficiency

Table 5.7 shows the potential for quantitative UWE in some Brazilian cities by implementing vehicle wash water reclamation. This activity represents 0.3 to 0.7% of the total domestic demand for the studied cities, being greater in richer cities (Curitiba, Porto Alegre, Brasilia and São Paulo) and lower in poorer regions (Salvador and Recife). These data seem to be low when compared to those for rainwater harvesting. Domènech et al. (2011) reported that rooftop rainwater harvesting in the metropolitan area of Barcelona could potentially meet approximately 16% of the total domestic water demand.

Although rainwater harvesting systems appear to have a much higher impact on quantitative UWE than vehicle wash wastewater reclamation, it is limited to regions with higher rainwater demand (Ghisi et al., 2007; Abdulla and Al-Shareef, 2009), which is not the case for many Latin American cities – Santiago Cl and Lima PE.

Moreover, the qualitative UWE results in

Table 5.8 show that water reclamation in vehicle washes can strongly diminish the pollution load on water resources or on WWTP. The savings in the municipal emission load for COD, NTK and phosphorus are low (<1%), but surfactants cannot be neglected - approximately 2.5%.

Table 5.7. Potential for quantitative UWE in different cities in Brazil – Vehicle-wash wastewater reclamation.

	Urban water demand, km^3/year	Vehicle wash demand, km^3/year	Water savings in vehicle washes, km^3/year	Quantitative UWE, %
São Paulo	7.98E-1	6.07E-3	4.66E-3	0.58
Salvador	1.89E-1	7.72E-4	5.98E-4	0.31
Brasilia	1.82E-1	1.23E-3	9.41E-4	0.51
Curitiba	1.25E-1	1.16E-3	8.89E-4	0.71
Recife	1.09E-1	4.84E-4	3.73E-4	0.34
Porto Alegre	1.02E-1	6.05E-4	4.62E-4	0.45

Table 5.8. Potential for qualitative UWE in Brazil (average results for the studied cities) – Vehicle wash wastewater reclamation.

	Urban load, ton.year^{-1}	Vehicle wash load, ton.year^{-1}	Savings, ton.year^{-1}	Qualitative UWE, %
COD	647,340	3,633	3,451	0.5
Surfactants	6,021	156	149	2.5
NTK	60,217	137	131	0.2
Phosphorus	10,538	63	60	0.6

5.3.2. Reclamation system

The results of the full-scale reclamation system are shown in

Table 5.9. The characterisation of wastewater and reclaimed water is presented in Table 5.10 (adapted from Zaneti et al., 2011). The total water volume used was 27 times the storage capacity (27 water cycles). The water consumption per wash was in the same range as that already reported (Al-Odwani et al., 2007; Boussu et al., 2007; Hamada and Miyazaki, 2004; Brown, 2002), and the results show that this system meets some strict water regulations from developed countries regarding the amount of fresh water used per vehicle (Boussu et al., 2007; QWC, 2008). The percentage of water reclaimed was close to 70%, and it is believed that automatic washing (in-bay or tunnel) rather than by-hand washing will produce a greater reclamation percentage.

The characterisation of wastewater and reclaimed water is presented in Table 5.10 (adapted from Zaneti et al., 2011). The mean values presented demonstrate the high efficiency of the process in reducing TSS (91%) and turbidity (91%). The total coliform and *E. coli* concentrations were reduced by 95% and 99% (2 log removal), respectively.

Table 5.9. Reclamation system results.

Week	Total used water, m^3	Number of water cycles	Number of washes	Average total water, $L.vehicle^{-1}$	Average fresh water, $L.vehicle^{-1}$	% Water Reclamation
1	10.1	1	91	11	48	57
2	14.6	2.5	137	107	59	45
3	14.8	4	125	118	42	64
4	16.3	5.6	152	107	39	64
5	7.9	6.4	63	125	40	68
6	11.6	7.5	113	103	29	72
7	10.4	8.6	89	117	35	70
8	11.7	9.7	112	104	36	66
9	11.8	10.9	93	127	33	74
10	15.1	12.4	127	119	30	75
11	9.7	13.4	86	113	37	67
12	16.5	15.1	133	124	30	76
13	7.2	15.9	59	122	35	71
14	11.8	17	84	140	38	73
15	19.7	18.9	141	140	34	76
16	17	20.6	99	172	33	81
17	10.1	21.6	68	149	39	74
18	13.5	23	80	169	69	59
19	20.1	25	107	188	101	46
20	23.6	27.4	136	174	75	57
Average and totals	274	27	2095	131	42	67

Table 5.10. FCF-SC process: Characterisation of wastewater and reclaimed water (mean values ± 1/2 standard deviation).

Parameters	**Wastewater**	**Reclaimed water**	**Examination Methods***
pH	7.4 ± 0.8	7.3 ± 0.5	-
TSS, $mg.L^{-1}$	89 ± 54	8 ± 6	2540 D
TDS, $mg.L^{-1}$	344 ± 25.5	388 ± 42	-

Turbidity, NTU	103 ± 57	9 ± 4	2130 B
Total coli forms, CFU/100 mL	3.1E ± 5	3.3E ± 4	9223 B
E. coli, CFU/100 mL^{-1}	2.1E ± 4	7.4E ± 2	9221 E

*APHA, 2005.

5.3.3. Microbiological and chemical risk assessments

The microbial risks that users and operators are exposed to in different washing schemes are presented in Table 5.11. According to Haas (1996), a risk threshold of 10^{-4} (1 person infected in 10,000) "may be far too stringent", given that waterborne illness caused by public water supply in the United States, for example, may be as high as 10^{-2}. Some authors report that a risk of 10^{-3} is commonly used as an acceptable risk for recreational water (FDEP, 1998; Metcalf & Eddy, 2006). Therefore, this value can be adopted for vehicle wash activities, considering the lower exposure of individuals to reclaimed water in vehicle washes.

The results presented in Table 5.11 show that the risk of infection for users (customers) is always below 10^{-3}. Nevertheless, when utilising wastewater without any treatment, the risk for operators in both washing schemes is consistently greater than the accepted threshold. Therefore, water reclamation in vehicles wash must be preceded by a disinfection step, and *E.coli* counts must be controlled. The microorganism inactivation study shows that a limit of 200 CFU.100 mL^{-1} or lower is reached with an initial chlorine dose of 15 $mgCl_2.L^{-1}$ and a reaction time of 2 hours.

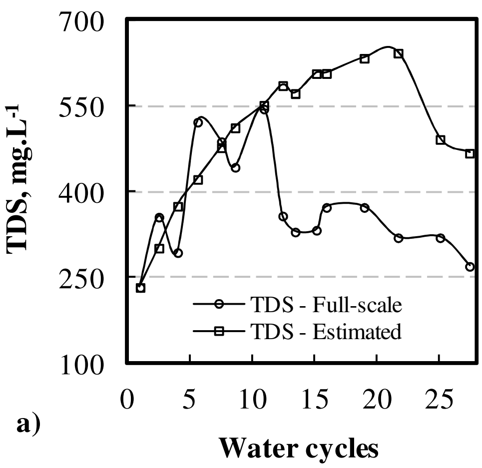
Table 5.11. Microbiological risk assessment for different individuals and washing schemes for vehicle washes. Automatic refers to in-bay and conveyor washing schemes.

Individual	Washing scheme	Route	Water	*E. coli*, CFU.100 mL^{-1}	V^*	N^{**}	Frequency of Exposure	Annual risk***
User	By-hand	Aerosol	Wastewater	2,1E+04	0,1	3	Once a week	1,7E-05
Operator	By-hand	Aerosol	Wastewater	2,1E+04	0,1	315	15 washes per Day	1,0E-02
Operator	By-hand	Ingestion	Wastewater	2,1E+04	1,0	3150	15 washes per Day	1,0E-01
User	Automatic	Aerosol	Wastewater	2,1E+04	0,1	3	Once a week	1,7E-05
Operator	Automatic	Aerosol	Wastewater	2,1E+04	0,1	2100	100 washes per Day	6,9E-02
Operator	By-hand	Ingestion	Suggested reclaimed	2,0E+02	1,0	30	15 washes per Day	1,0E-03

			water					
Operator	Automatic	Aerosol	Suggested reclaimed water	3,0E+02	0,1	30	100 washes per Day	1,0E-03

*Volume ingested per exposure;
**CFU ingested/day;
***Extrapolation of daily risk.

Regarding the chemical risks of reclaimed water, Figure 2a shows that the TDS concentration estimated by the proposed mass balance was always higher than the TDS concentration during the full-scale study, though they both show a similar tendency. Furthermore, there was no remarkable difference in the TDS concentration when utilising PAC+flocculant rather than Tanfloc SL (Figure 2b). By comparing the TDS concentration for 70% and 80% recycling percentages, a marked difference was observed, but the mark of 1,500 mgTDS.L^{-1} (1,000 mgTDS.L^{-1} is the potable water standard in Brazil) was never reached. Figure 2c shows the concentration of Cl^{-} as a function of coagulation-flocculation reagents, the water recycling rate, and the number of water cycles. The maximum chloride concentration observed was 332 mg.L^{-1}, which is lower than the limit of 400 mg.L^{-1}, proposed by Nace (1975), suggesting that chloride is not a limiting factor.



a)

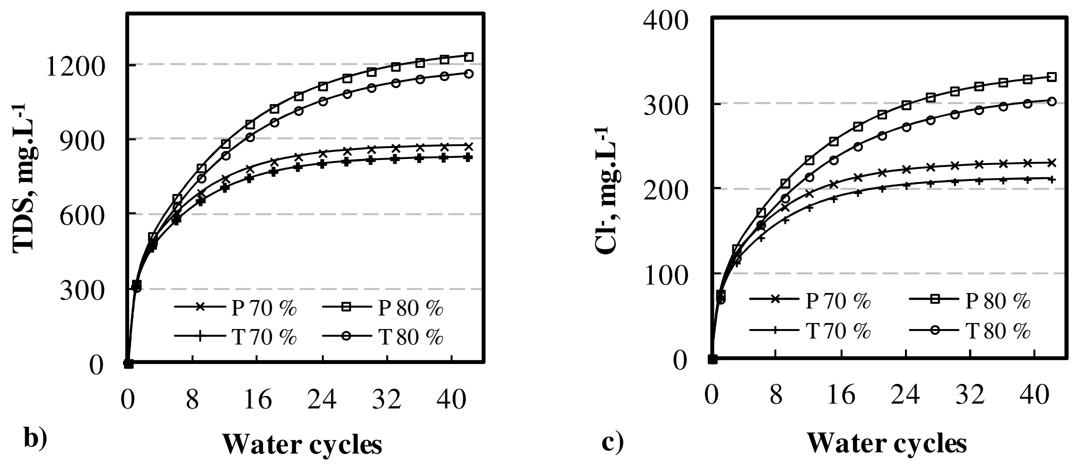


Figure 5.2. TDS and Cl^- concentrations as a function of water cycles - (a) TDS concentration in the reclaimed system (full-scale) and estimated by the mass balance (Equations 1,2, 3 and Table 2); (b) and (c) TDS and Cl^- estimated by the mass balance for different scenarios; P = PAC+flocculant; T = Tanfloc SL. Adapted from Zaneti et al. (2011[b]).

5.3.4. Economic assessment

Figure 5.3 shows that FCF amortisation in Brazil is strongly dependent on the price of fresh water and water demand: the amortisation period decreases with an increase in the price of water and demand. Because the water prices in Brazil reach high values, varying from US$ 3.6 to 13.3, the implementation of vehicle wash wastewater reclamation seems promising. In some of the evaluated scenarios, less than 5 months are required for FCF payback. Nonetheless, this period may rise to more than 50 months.

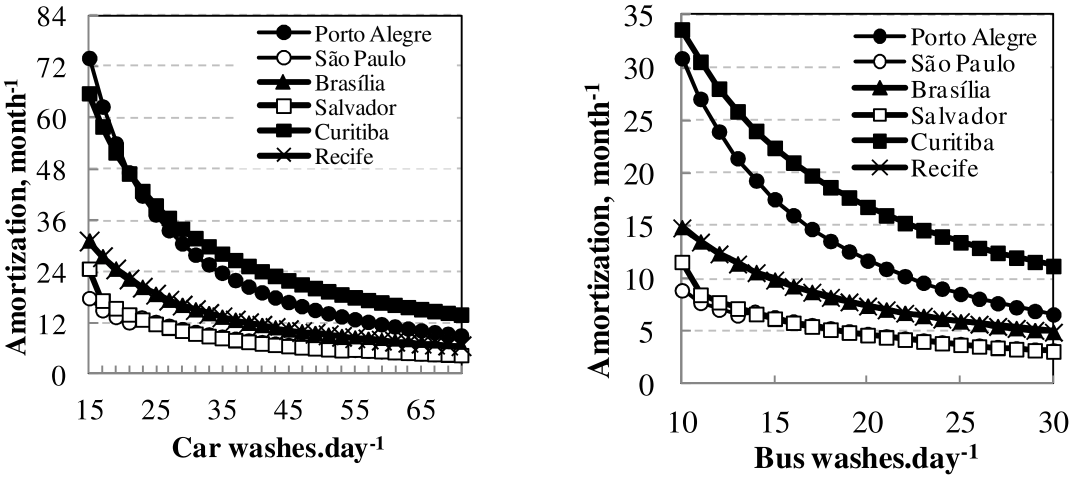


Figure 5.3. Amortisation of FCF equipment as a function of daily washes – (a) cars and (b) buses.

5.4. Discussion of FCF application for car wash water reclamation in Brazil

In Brazil, vehicle wash wastewater reclamation has not yet become common practice. Although water prices in the country are relatively high, compared to those in Spain (Domènech et al., 2011) and other developed countries, the lack of local regulations and partial economic subsidies appear to limit the practice. Users' motivation to install decentralised systems today is pecuniary, and thus, installation of these systems is restricted to units with higher water demand that can obtain financial benefits with reclamation technologies in the very short term. In this sense, it is apparent from the European (Partzsch, 2009), Australian (QWC, 2008) and North American (cities of Denver, Seattle and San Antonio) experiences that financial assistance must be coupled with technical support, new legislation and strict environmental monitoring.

The FCF process has been newly applied for vehicle wash water reclamation in southern Brazil and has shown to be capable of providing reclaimed water that meets an acceptable aesthetic quality with controlled microbial and chemical risks. The effectiveness of this process, in addition to the short payback periods, makes its application very promising. Evaluating the FCF as an innovative decentralised - "eco-friendly" - technology, and considering that almost 30 units are now operating in bus and other vehicle companies in the Metropolitan area of Porto Alegre, it can be concluded that, by now, some stages of the innovation chain have been overcome, namely, the basic and applied R&D and demonstration.

The actual status of the maturity of FCF innovation is pre-commercialisation. At this stage (Foxon et al., 2005), policy incentives such as certification programs and rebates/grants, which according to the North American and German experiences improve risk/reward ratios, are strongly recommended. These actions, as well as the involvement of larger players (for example, large Brazilian petro station companies), may create and support an early niche market and multiply the number of units in vehicle washes operating with water reclamation systems over shorter periods.

5.5. Conclusions

The results obtained from the present study suggest that water reclamation in vehicle washes may help increase the efficiency of urban water use by reducing water demand by 0.3 – 0.7% and diminishing pollution pressure in water resources, mainly by eliminating 2.5% of the surfactant load. Full-scale flocculation-column flotation (FCF) studies showed that almost 70% of odourless and clear (average turbidity of 9 NTU) water was reclaimed in a car wash over 27 water cycles by utilising a low-cost/controlled-risk technology. Meanwhile, bench-scale studies and theoretical calculations using a microbiological-risk model indicated that car wash users were not at risk, and a limit of 200 CFU.100 mL^{-1} (reached with a chlorine dose of 15 mg.L-1) of *E. coli* was suggested for an acceptable microbiological risk regarding car wash operators. The chloride and TDS residual concentrations estimated by mass balance stabilised below 350 $mg.L^{-1}$ and 900 $mg.L^{-1}$, respectively, indicating that water was reclaimed with controlled chemical risk. The payback period of FCF equipment is dependent mainly on water prices and wash demand and can be shorter than one year. Looking towards the future, this technology may became a reality in Brazil and elsewhere, especially if public policies regarding the improvement of risk/reward ratios for investors and the involvement of large players (for example, large Brazilian petro station companies) are implemented.

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6. Conclusões

As principais conclusões do trabalho são:

1. A técnica de floculação-flotação em coluna (FFC) foi desenvolvida e teve suas principais unidades constituintes avaliadas a partir de estudos básicos. Os estudos de desenvolvimento da técnica foram realizados utilizando o efluente de lavagem de veículos como modelo e mostraram sua viabilidade. Foram atingidas taxas de aplicação na separação sólido/líquido de até 25 $m.h^{-1}$, com processo estável e alta eficiência de clarificação do efluente (< 90% de redução de turbidez do efluente);

2. O processo FFC, seguido de filtração em areia e cloração, foi aplicado e monitorado em um lava-rápido em Porto Alegre durante 20 semanas ininterruptas. Os resultados mostraram um consumo total de água por lavagem de 131 L, sendo 40 L de água nova, apontando assim para uma economia média de 70% de água nova;

3. A água tratada pelo processo FFC+filtração em areia+cloração (a partir de hipoclorito de sódio - 0,5 $mgCl_2.L^{-1}$) foi sempre clarificada, livre de odor pronunciado e de cor e alguns parâmetros de interesse ambiental como demanda de oxigênio (DBO e DQO), nutrientes (nitrogênio e fósforo), surfactantes e óleos e graxas não mostraram aumento de sua concentração ao longo dos ciclos da água no sistema de reciclagem. Por outro lado, sólidos dissolvidos totais e cloretos mostraram uma leve tendência de aumento das suas concentrações, mostrando a necessidade de uma avaliação mais criteriosa do seu balanço de massa no sistema. Nesta condição de cloração (0,5 $mgCl_2.L^{-1}$), ocorreu a presença de *E.coli* na água tratada, fazendo-se necessária uma avaliação do risco microbiológico;

4. Os usuários (clientes) do lava-rápidos estudado não correriam risco significativo mesmo se o efluente da lavagem dos veículos fosse reciclado sem qualquer tratamento. Entretanto, neste caso, os operadores da lavagem estariam correndo um risco 100 vezes maior que o aceitável;

5. Foi estimado uma contagem limite de 200 *E.coli* NMP.100mL^{-1} na água de reúso para que o risco microbiológico esteja controlado em lavagens manuais, enquanto que uma contagem de 300 *E.coli* em NMP.100mL^{-1} seria aceitável em água de reúso em lavagens automatizadas (tipo túnel, roll-over). Estes limites, no sistema estudado, foram atingidos com a dosagem de 15 mgCl_2.L^{-1};

6. A estimativa da concentração de sólidos dissolvidos totais – SDT e cloretos – Cl^- foi realizada com uso de um balanço de massas. O balanço de massas proposto foi verificado utilizando-se os dados reais de monitoramento do sistema ao longo do estudo e mostrou adequado ajuste aos dados reais;

7. Foi estimado um consumo de água na atividade de lavagem de veículos de 7,9 milhões de m³.ano^{-1}, somente nas seis principais capitais de estado do pais, volume este equivalente a aproximadamente 0,5% do consumo total de água nestas mesmas cidades;

8. Os surfactantes foram determinados como sendo o poluente mais pronunciado no efluente da atividade de lavagem de veículos e nas seis principais capitais de estado do pais foi estimada uma massa emitida de 149 toneladas.ano^{-1}, massa esta equivalente a 2,5% do total emitido por estas cidades;

9. A avaliação econômica da prática mostrou uma alta viabilidade de implementação do sistema proposto na maioria das capitais brasileiras consideradas – quanto maior a demanda por lavagens, maior a viabilidade econômica

10. Acredita-se que a informação técnica resultante desta tese, seja utilizada na elaboração de regulamentações que obriguem a reciclagem de água na lavagem de veículos. Esta obrigatoriedade e outros instrumentos de política pública, como incentivos fiscais, devem ser implementados, criando um nicho de mercado inicial para a pratica de reúso de água em ambientes urbanos;

11. Existem comercialmente unidades baseadas neste estudo, com benefícios à UFRGS e à sociedade (controle de poluição e geração de renda).

7. Sugestões para trabalhos futuros

1. O processo FFC seguido de filtração em areia e cloração deverá ser estudado, aplicado e avaliado em outros serviços urbanos, como por exemplo: na lavagem de roupas (hotéis, hospitais, restaurantes e indústria), na lavagem de plástico para reciclagem (PET, PP, PE, entre outros) e no reúso de águas cinza leves. A qualidade necessária à água de reúso para algumas destas atividades é descrita em *guidelines* nacionais (ANA, 2005; ABNT NBR 13.969) e internacionais (USEPA, 2004; Metcalf & Eddy, 2006). Entretanto, um tratamento complementar ao FFC+filtração em areia+cloração pode ser requerido;

2. O polimento da água tratada com processos oxidativos e oxidativos avançados, por exemplo estes que envolvem o uso de ozônio, pode ser interessante. O Apêndice II apresenta alguns resultados preliminares de polimento da água tratada via FFC+filtração em areia com ozônio. Na atividade de lavagem de veículos este polimento mostrou melhorar sensivelmente o aspecto estético e a qualidade da água de reúso (geração de espuma e odor);

3. Diversos estudos têm sido realizados utilizando processos físico-químicos como pré-tratamento a sistemas de membranas – os chamados sistemas híbridos. Acredita-se que o processo FFC tem grande potencial para ser empregado em conjunto com as membranas, viabilizando água de reúso com qualidade bastante elevada;

4. O lodo gerado com a técnica proposta não foi objeto de estudo na presente tese e um estudo criterioso da quantidade gerada, características e possibilidade de co-processamento ou estabilização deve ser disponibilizado. Alguns resultados e discussões preliminares são mostrados no Anexo II.

8. Referências

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Apêndice I. Resíduos sólidos gerados em sistemas de reciclagem de água na lavagem de veículos

Em lavagem de veículos convencionais ocorre geração de resíduos sólidos na pista de lavagem, a chamada “areia de pista”. Nos sistemas de lavagem que contam com reciclagem de água via processo FFC, ocorre ainda a geração de lodo no tratamento.

A caracterização destes resíduos foi realizada no lava-rápido onde foram realizados os estudos – Ecoagua Serviços de Lavagem Ltda. A Tabela abaixo mostra os resultados mais relevantes desta caracterização. Os resultados expressão a concentração de poluente no resíduo em partes por milhão (ppm), ou seja, a massa de poluente (em mg) pela massa do resíduo (em kg). Os parâmetros avaliados foram os citados na resolução CONAMA 420/2009 e identificados como passíveis de ocorrência na atividade de lavagem de veículos – TPH, BETEX, VOC (poluentes orgânicos) e metais pesados (poluentes inorgânicos).

Resultados mais relevantes da caracterização dos resíduos sólidos gerados na lavagem Ecoagua em Porto Alegre

	Antimônio, $mg.kg^{-1}$	**Cobre, $mg.kg^{-1}$**	**TPH, $mg.kg^{-1}$**	**Valores orientadores* CONAMA 420/2009**
Areia de pista	6,3	70	-	10
Lodo	102	1150	0,05	400
A/L – 4/1	7,2	83	3710	< 300

*Valores orientadores para solos em investigações de áreas residenciais.
A - Areia da pista de lavagem
L - Lodo

Os resultados da caracterização dos resíduos mostraram concentrações elevadas de metais pesados no lodo (Antimônio e cobre – amostras L1 e L2 do anexo 1), mas não na areia da pista de lavagem (Amostras A1 e A2 do anexo 1). Por outro lado, a concentração de TPH no lodo foi baixa, mas alta na areia da pista de lavagem. Foram realizadas misturas do lodo (L) e da areia da pista de lavagem (A) na proporção observada na Ecoagua (1 parte de Lodo e 4 partes de Areia). Este procedimento possibilitou a redução da concentração de antimônio e cobre a valores inferiores aos valores orientadores para investigação em solos de ambientes residenciais e industriais (CONAMA 420/2009). De qualquer forma, a concentração de TPH continuou acima do aceitável.

Para redução dos TPH, pode-se realizar processo de biorremediação. Este procedimento ocorre hoje em escala industrial no estado do Rio Grande do Sul e em quase todo território nacional. Um exemplo de empresa que presta serviço de biorremediação de solos contaminados é a Purus Soluções Ambientais em Canoas/RS - http://www.purus.com.br. A empresa possui licença da FEPAM para dispor o resíduo após biorremediação como material de preenchimento em obras, ou como material de cobertura de aterros sanitários.

A partir destes resultados preliminares, pode-se observar a necessidade de maiores e melhores estudos neste tema de caracterização do lodo gerado pelo FFC.

Apêndice II. Polimento da água tratada via FFC com ozônio

Os resultados preliminares do polimento da água tratada via FFC+filtro de areia com ozônio mostram que a concentração de surfactantes pode ser drasticamente diminuída, assim como uma elevada desativação de coliformes Totais e *E.coli* pode ser atingida. Os resultados disponíveis até o momento, apresentados nas Tabelas abaixo, são fruto de estudos em bancada e piloto em um posto de lavagem de veículos de passeio localizado em Porto Alegre, que conta com sistema de reciclagem de água e equipamento FFC+filtro de areia.

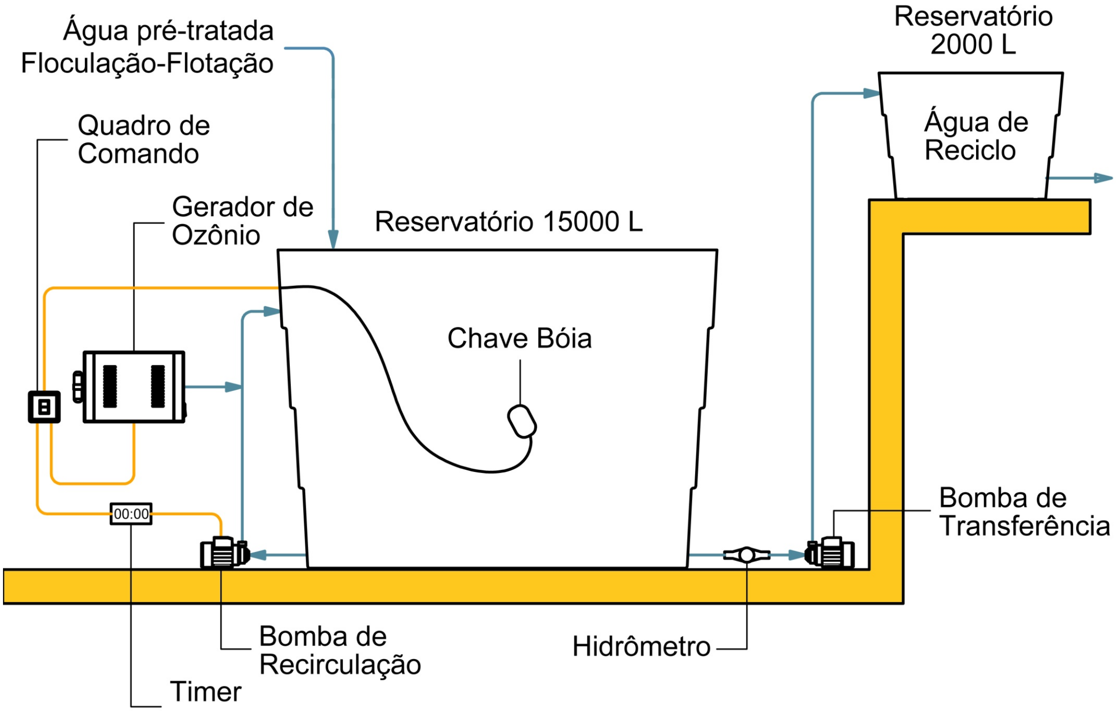
Nos estudos em escala de bancada, 1 L da água tratada via FFC+filtro de areia foi disposto em um frasco lavador, onde o gás de ozônio foi borbulhado. Nos estudos em escala piloto, a água trada foi recirculada a partir de um tanque de 15.000 L. O ozônio foi injetado na corrente líquida com auxilio de um dispositivo Venturi, instalado no ramal de recalque da bomba centrifuga de recirculação – veja Figura abaixo. Em ambos os estudos, o gerador de ozônio utilizado (marca OZ Engenharia, com capacidade nominal para geração de 4 $gO_3.h^{-1}$) foi calibrado por iodometria, apontando produção de 3,6 $gO_3.h^{-1}$.

Resultados dos estudos de ozonização do efluente do processo FFC em bancada. Valores médios – n = 2.

	Bruto	**Flotado**	**10 min.**	**30 min.**	**60 min.**	**120 min.**
pH	6,4	6,9	6,3	6,1	6,2	4,1
Turbidez, NTU	200	18	3	2	1	1
E.coli, $NMP.100mL^{-1}$	660	4,7E+02	1,8E+00	1,8E+00	1,8E+00	1,8E+00
DBO, $mgO_2.L^{-1}$	157	130	99	69	59	69
DQO, $mgO_2.L^{-1}$	376	292	184	139	144	129
Condutividade, $\mu s.cm^{-1}$	800	1024	853	784	859	1015
Sulfeto, $mgS_2.L^{-1}$	3,9	1	0,6	0,7	0,7	0,6
Surfactantes, $mgMBAS.L^{-1}$	5	4,4	1,6	0,5	0,2	0,2

Resultados dos estudos de ozonização do efluente do processo FFC em escala piloto. Valores médios – n = 5.

Parâmetro	Unidade	Bruto			Flotado			Ozonizado		
		Mínimo	**Máximo**	**Média**	**Mínimo**	**Máximo**	**Média**	**Mínimo**	**Máximo**	**Média**
Turbidez	NTU	194	254	229	13	28	21	4	18	10
E.coli	NPM/100mL	4,5E+01	2,4E+03	1,2E+03	1,8E+00	4,5E+01	1,7E+01	1,8E+00	1,8E+00	1,8E+00
Coliformes Totais	NPM/100mL	1,6E+06	1,3E+07	5,3E+06	2,4E+04	2,4E+06	6,3E+05	1,3E+04	8,4E+04	3,6E+04
DBO_5	mg/L O_2	202,9	495,8	396,9	106,3	415,5	289,9	2,0	122,2	60,5
DQO	mg/L O_2	249	873	683	129	536	415	12	167	96
Sulfetos	mg/L S^{2-}	3,9	5,1	4,8	1,0	2,2	1,5	0,1	1,0	0,6
Condutividade	$\mu S.cm^{-1}$	730	1530	933	879	1332	1149	1045	1125	1068
Surfactantes	mg/L MBAS	11,26	22,27	14,60	2,46	4,93	4,15	0,03	4,29	1,26



Esquema ilustrativo do processo de ozonização da água tratada via FFC+filtração em areia por recirculação instalado em um posto de lavagem de veículos de passeio.

A utilização do ozônio no polimento da água tratada via FFC+filtro de areia proporcionou ganho nas principais características de interesse da água tratada. A água tratada após ozonização apresentou maior clarificação, uma vez que a turbidez diminui e os sólidos em suspensão foram removidos. Em bancada, a diminuição de turbidez foi superior a 80%, em relação à água tratada por FFC+filtro de areia e nos estudos piloto turbidez inferior a 5 NTU foi atingida. Assim como na clarificação, ocorreram ganhos em outros aspectos estéticos da água ozonizada – odor e excesso de espuma. A concentração de sulfeto nos estudos piloto foi diminuída em pelo menos 75%, enquanto os surfctantes MBAS foram diminuídos em até 99,99%.

Um ganho notável da ozonização foi a eficiente desinfecção da água tratada. Em todos os ensaios realizados em escala de bancada e piloto os *E.coli* foram totalmente desativados, indicando uma segurança microbiológica bastante elevada da água ozonizada.

Por fim, pode-se comentar da redução de condutividade observada na água tratada após ozonização. A condutividade é uma indicação direta da presença de sais e sólidos dissolvidos. Estes poluentes mostram tendência de aumento de concentração em sistemas de reúso/reciclagem de água, inclusive na atividade de lavagem de veículos, como foi observado no presente trabalho. A diminuição no aumento da concentração de sólidos dissolvidos no sistema de reciclagem de água pode ser um ganho indireto do polimento da água tratada via FFC+filtro de areia com ozônio. Mais estudos devem ser realizados para determinar os mecanismos que explicam esta tendência.