Technical Guidelines

PAC/MF
powdered activated carbon / ceramic microfiltration for drinking water production
Title
Technical Guidelines of PAC/MF – Powdered Activated Carbon/Ceramic Microfiltration for Drinking Water Production

Deliverable identification
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Scope and objectives

These technical guidelines provide guidance on the use of the hybrid process of powdered activated carbon adsorption and ceramic microfiltration for sustainable drinking water production.

They were developed based on the field demonstration of the technology, in Portugal, with a pilot prototype, within the LIFE Hymemb project LIFE12 ENV/PT/001154 “Tailoring hybrid membrane processes for sustainable drinking water production”, conducted by LNEC – the National Civil Engineering Laboratory and Águas do Algarve, S.A.

After a brief introduction of the relevant terms and definitions and of the fundamentals of powdered activated carbon adsorption and ceramic microfiltration, the potential of the innovative hybrid PAC/MF process is presented.

Answers to when, where and how using the technology are then addressed aiming at an easy and comprehensive use by water practitioners, design engineers, water regulators, academia and students of different backgrounds. “When” identifies the opportunities for using PAC/MF technologies, whether for upgrading conventional WTPs or as an alternative treatment; “Where” identifies the key water quality criteria for its use and recommends pretreatment sequences; “How” guides the design and the operation of the technology.

The full set of equations needed for the economic analysis of this process is then comprehensively derived and the results obtained for the scenarios demonstrated in LIFE Hymemb are provided.

These guidelines, with adaptations, may assist the use of PAC, ceramic MF or PAC/MF for other contaminants than those targeted by LIFE Hymemb, as well as for other applications, e.g. for water reclamation aiming at safe unrestricted water reuse.

Each “when”, “where” and “how” sections are labelled with different colours and within each section, or subsection, three different, and increasing, shades are used: the first establishing the background (lighter), the second presenting the LIFE Hymemb results and the third showing the highlights (darker), as shown below.
Terms and definitions

**Adsorption** – the physical mass transfer operation in which the adsorbent, a highly porous material of high surface area (typically 150-1400 m²/g, depending on the adsorbent material), uptakes the adsorbates from a liquid or gaseous stream; in water treatment, the adsorbent is usually activated carbon (typically 600-1200 m²/g) and the adsorbates are organic and inorganic contaminants, often microcontaminants, dissolved in the water to be treated. This uptake occurs due to chemical activity gradients and preferential affinity of the adsorbates towards the solid interface, often by hydrophobic, electrostatic, polar, acid-base, Van-der-Walls or other intermolecular interactions.

**Backwash** – the maintenance operation of membrane hydraulic cleaning that typically involves periodic reverse flow to remove the material (often fouling agents, or foulants) accumulated at the membrane surface or pores.

**Chemically enhanced backwash (CEB)** – the maintenance operation of membrane cleaning which involves 3 steps: the hydraulic backwash, the membrane soaking with a chemical solution and a final hydraulic backwash.

**Clean-In Place (CIP)** – the infrequent (typically 1-2 times/year) and longer (typically a 24-h duration) application of a chemical solution (or series of solutions) to a membrane unit for the intended purpose of removing accumulated foulants that could not be removed by backwash or CEB.

**Cross-flow filtration** – the filtration mode in which the flow is tangential to the membrane surface and the feed water is partially recirculated.

**Dead-end filtration** – the filtration mode in which all the water that enters the membrane surface is pressurized to pass through the membrane.

**Filtrate (permeate)** – the water produced from a filtration process.

**Filtration time (and backwash frequency)** – the filtration time is the duration of a filtration cycle between two backwashes or a backwash and a CEB and defines the backwash frequency, i.e. once per filtration time.

**Flux (J, L/(m².h))** – the filtrate (or permeate) flow rate per unit of membrane filtration area.

**Fouling** – the gradual accumulation of contaminants on the membrane surface or within its porous structure that inhibits the passage of water, thus decreasing the membrane productivity.

**Fouling agents or foulants** – the materials (contaminants) that are responsible for the membrane fouling.

**Fouling rate (FR, mbar/h or mbar/d)** – the transmembrane pressure (TMP) variation over time. It can be calculated for a filtration cycle (fouling rate within cycles, FRw), between filtration cycles, thus taking into account the backwash (fouling rate between cycles, FRb), or between sets of filtration cycles with a CEB in between (fouling rate between cycles with CEB, FRc).
Inlet pressure (or intake pressure) \( (P_{\text{feed, bar}}^{\text{in}}) \) – the feed stream pressure at the membrane inlet.

Microfiltration (MF) – the pressure-driven membrane filtration process that typically employs membranes with a pore size range of 0.05 – 0.8 \( \mu \text{m} \). Throughout this document, the term microfiltration is used as ceramic microfiltration.

Mixing gradient \( (G, \text{s}^{-1}) \) – the mean velocity gradient for mixing.

PAC contact time – the time-period during which PAC is in contact with the adsorbates (water contaminants).

PAC/MF – the hybrid process combining powdered activated carbon (PAC) and microfiltration (MF). Throughout this document, only ceramic microfiltration is considered.

Permeability \( (M, \text{L/(m}^2\cdot\text{h.bar)}) \) – Pressure normalised flux (also termed specific flux).

Permeate (or filtrate) – the water that passes through a membrane.

Plant downtime \( (\text{min/day}) \) – the time the plant is offline for backwashing, CEB, integrity testing and routine maintenance.

Pore Size (\( \mu\text{m} \)) – the size of the openings in a porous membrane expressed either as nominal (average) or the absolute (maximum) value.

Powdered activated carbon (PAC) – a form of carbon processed to have small, low-volume pores that increase the surface area available for adsorption and with particle diameters typically of less than 177 \( \mu \text{m} \), the lower the PAC diameter is the faster the kinetics but the poorer its retention by sedimentation or sand filtration. The PAC typical size therefore depends on the downstream solid-liquid separation - for conventional PAC application and separation by sedimentation, PACs > 20 \( \mu \text{m} \) are used, whereas for the PAC/MF process, PACs < 20 \( \mu \text{m} \) are often used.

Pretreatment – any treatment applied to the feed water to a membrane process to achieve desired water quality objectives and/or protect the membranes from damage or fouling.

Rejection (%) – the prevention of feed water constituents from passing through a semi-permeable membrane; the fraction of solute held back by the membrane.

Treatment capacity \( (\text{m}^3/(\text{m}^2\cdot\text{day.bar})) \) – the effective amount of filtered water that can be produced by membrane area, time unit and intake pressure.

Transmembrane pressure (TMP) – the pressure gradient across the membrane (feed and permeate sides) and the driving force for water transport across a microporous membrane.

Water recovery rate (or water recovery or recovery) – the amount of feed water that is converted into product water, expressed as a percentage.
Symbols and abbreviations

\( A_m \) – Membrane area (m)

CEB – Chemically enhanced backwash

CFS – Coagulation/Flocculation/Sedimentation

DOC – Dissolved organic carbon (mg C/L)

FR – Fouling rate

FRb – Fouling rate between cycles (mbar/h)

FRc – Fouling rate between cycles with CEB (mbar/day)

FRw – Fouling rate within cycles (mbar/h)

G – Velocity gradient for mixing (s\(^{-1}\))

J – Flux (L/(m\(^2\).h))

\( M_{20} \) – Specific flux (L/(m\(^2\).h.bar))

MF – Microfiltration

NF – Nanofiltration

NOM – Natural organic matter

PAC – Powdered activated carbon

PAC/MF – Hybrid process of powdered activated carbon/ceramic microfiltration

\( P_{\text{feed}}^{\text{in}} \) – Feed stream pressure at the membrane inlet (or intake pressure) (bar)

\( P_{\text{feed}}^{\text{out}} \) – Feed stream pressure at the membrane outlet (bar)

PhC – Pharmaceutical compound

Q\(_f\) – Feed flow rate (L/h)

Q\(_p\) – Permeate flow rate (plant capacity) (L/h)

R – Water recovery rate (%)

RO – Reverse osmosis

SUVA – specific UV absorbance at 254 nm (L/(mg C.m))

\( t_c \) – PAC contact time (h)

TCF – Temperature correction factor (-)

TMP – Transmembrane pressure (bar)

TOC – Total organic carbon (mg C/L)

\( V_{bw} \) – Backwash volume (L)

\( V_{\text{CEB}} \) – CEB volume (L)

\( V_p \) – Permeate volume (L)

\( \eta \) – Motor efficiency (-)
Technical Guidelines of PAC/MF for Drinking Water Production

The PAC/MF concept

PAC/MF is the hybrid process combining powdered activated carbon (PAC) adsorption and microfiltration (MF).

Adsorption is the physical mass transfer operation in which the adsorbent, a highly porous material of high surface area, uptakes the adsorbate(s) from a liquid or gaseous stream. In water treatment, the adsorbent is usually activated carbon and the adsorbates are organic and inorganic contaminants, often microcontaminants, dissolved in the water to be treated. This uptake occurs due to chemical activity gradients and preferential affinity of the adsorbates towards the solid interface, often by hydrophobic, electrostatic, polar, acid-base, Van-der-Walls or other intermolecular interactions.

Activated carbons are manufactured from coconut shell, peat, hard and soft wood, lignite coal, bituminous coal, olive pits and various carbonaceous specialty materials. By subjecting the raw carbon to activation process of oxidation with agents such as air, steam, or oxygen, at high temperatures, its internal structure is further eroded creating an even greater surface area. Both the raw material and the activation conditions affect the activated carbon pore structure and surface chemistry and therefore its adsorbent behaviour.

Powdered activated carbons (PACs) are defined by the American Society Testing Materials (ASTM 1999) as activated carbon particles passing through an 80-mesh sieve (0.177 mm) and smaller. Activated carbon is an effective adsorbent because it is a highly porous material and provides a large surface area to which contaminants may adsorb (if we could unfold one gram of PAC it would equal anywhere from 600 m² to 1200 m²).

A typical PAC has a porous structure consisting of a network of interconnected macropores (> 50 nm in diameter), mesopores (2-50 nm), secondary micropores (0.8-2 nm) and primary micropores (< 0.8 nm) that provides a tremendous potential for the adsorption of organic molecules due to its high surface area. Activated carbon manufacturers have developed different activation processes so that they can control to a large degree the size of the pores, designing PAC to match the molecular sizes of the target contaminants.
A **membrane** is a physical barrier that separates two phases and selectively transfers mass between these phases. Membranes comprise a selective layer and a support and are thus much more selective than conventional filter media.

Membrane processes can be operated in two modes:

- **dead-end mode**, in which the feed flow is perpendicular to the membrane surface, allowing higher recovery rates and avoiding the need for feed recirculation;
- **cross-flow mode**, in which the feed flow is parallel to the membrane surface, then maintaining the contaminants in suspension, allowing a better fouling control but requiring additional feed recirculation.

There are four **membrane pressure-driven processes**: microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO).

**Microfiltration (MF)** is a low-pressure and safe barrier for particles, but does not retain dissolved organics and inorganics and viruses.
Ceramic MF membranes are better candidates for PAC/MF than polymeric ones due to their uniformity, strong chemical and physical resistance and low fouling potential, responsible for high fluxes at low pressures (< 1 bar), easy cleaning (e.g. allowing high doses of chlorine and ozone and vigorous backwash), high water recovery (> 95 %) and long lifetimes (2-5 times those of the polymeric membranes) and ability to process high solids loading, including PAC. The capital costs involve a higher initial investment but lower membrane replacement costs, and the operating costs are potentially lower due to their energy efficiency (< 0.1 kWh/m³).

The hybrid PAC/MF process combines synergistically the PAC and ceramic MF advantages, minimizing their limitations:

- Adsorption onto PAC is the key-step for the removal of low (< 300 Da) and intermediate molar mass contaminants (300 - 1000 Da) and viruses,
- MF is the absolute barrier against bacteria, protozoan (oo)cysts (Cryptosporidium oocysts and Giardia cysts, resistant to chemical oxidation), turbidity and fine PAC particles, allowing the use of finer PAC of faster kinetics and also PAC recirculation, i.e. lower doses and no risk of residual water turbidity occurring from PAC fines in the treated water. It has an excellent resilience to raw water quality fluctuations.

PAC/MF process is highly flexible and allows an easy adjustment to seasonal problems (e.g. cyanotoxins) as PAC type and doses may be quickly changed according to the target contaminant(s) and intake water quality, and standalone MF (with no PAC addition) may be used when dissolved organics are not an issue.
PAC/MF, WHEN?

When should PAC/MF be considered a candidate treatment?

The contaminants targeted and the raw water characteristics determine the PAC/MF advantages over the alternative processes. Depending on the target contaminants...

PAC/MF may be applied for controlling regular contaminants, such as turbidity, natural organic matter (NOM) and microorganisms, but it is particularly valuable for contaminants that challenge the conventional water treatment plants (WTPs) and/or are potentially hazardous by toxic, mutagenic, endocrine disrupting action and development of antibiotic(s) resistant bacteria.

PAC/MF is therefore a good option for the safe control of:

- Microorganisms resistant to chemical oxidation (e.g. protozoan (oo)cysts);
- NOM and oxidation by-products (OBPs) (e.g. trihalomethanes, haloacetic acids);
- Dissolved microcontaminants of low-intermediate molar mass, namely pharmaceuticals, pesticides and cyanotoxins produced by toxic cyanobacteria.

The PAC adsorption of the contaminants determines their overall removal by PAC/MF and depends on the: i) contaminant structure (size, shape, charge, polarity, functional groups); ii) PAC characteristics (porous structure and surface chemistry); iii) water conditions (e.g. concentration of competing NOM).

<table>
<thead>
<tr>
<th>LIFE Hymemb</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Amenable to PAC/MF removal</strong></td>
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<tr>
<td><strong>Relatively amenable to PAC/MF removal</strong></td>
</tr>
<tr>
<td><strong>Pharmaceuticals</strong></td>
</tr>
<tr>
<td>Atenolol</td>
</tr>
<tr>
<td>Azithromycin</td>
</tr>
<tr>
<td>17β-estradiol</td>
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<tr>
<td>Bezlifibrate</td>
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<tr>
<td>Carbamazepine</td>
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<tr>
<td>Citroprofaxin</td>
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<tr>
<td>Estrone</td>
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<tr>
<td>Fluoxetine</td>
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<tr>
<td>Indomethacin</td>
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<td>Propranolol</td>
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<tr>
<td>Ramipril</td>
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<tr>
<td>Ranitidine</td>
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<tr>
<td><strong>Pesticides</strong></td>
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<tr>
<td>Chlortolurom</td>
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<tr>
<td>Diuron</td>
</tr>
<tr>
<td>Linuron</td>
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<tr>
<td>Tebuconazole</td>
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<tr>
<td><strong>Pharmaceuticals</strong></td>
</tr>
<tr>
<td>Diclofenac</td>
</tr>
<tr>
<td>Erythromycin</td>
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<tr>
<td>Ibuprofen</td>
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<tr>
<td>Ketoprofen</td>
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<tr>
<td>Lincomycin</td>
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<tr>
<td>Ofloxacin</td>
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<tr>
<td><strong>Pesticides</strong></td>
</tr>
<tr>
<td>Alachlor</td>
</tr>
<tr>
<td>Atrazine</td>
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<tr>
<td>Cymoxanil</td>
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<tr>
<td>Terbutylazine</td>
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<tr>
<td><strong>Less amenable to PAC/MF removal</strong></td>
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<tr>
<td><strong>Pharmaceuticals</strong></td>
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<tr>
<td>Amoxicillin</td>
</tr>
<tr>
<td>Cyclophosphamide</td>
</tr>
<tr>
<td>Paracetamol*</td>
</tr>
<tr>
<td>Sulfamethoxazole</td>
</tr>
<tr>
<td><strong>Pesticides</strong></td>
</tr>
<tr>
<td>Bentazon</td>
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<tr>
<td>Dimethoate</td>
</tr>
</tbody>
</table>

*Under high competition: low PAC dose (< 7 mg/L) and/or high(er) competitor concentration (other microcontaminants, NOM).

* Paracetamol removal was particularly sensitive to PAC dose, varying from 39% with 6 mg/L up to 96% with 13 mg/L PAC.
Cyanotoxins, pesticides, pharmaceuticals, oxidation by-products, taste and odour compounds

MF with in-line coagulation

NOM removal by PAC/MF depends on NOM characteristics, particularly size and hydrophobicity. PAC preferentially removes small hydrophobic compounds.

In LIFE Hymemb, an overall high removal of dissolved microcontaminants was observed (up to 98%), but individually the pharmaceuticals and pesticides presented a distinct behaviour and were therefore classified in three groups based on their amenability to be removed by PAC/MF: amenable, relatively amenable and less amenable to PAC/MF removal. The compounds less amenable to PAC/MF removal, such as the antibiotic sulfamethoxazole and the pesticide bentazone, were found to be good candidates for conducting challenging treatment tests in the WTPs and for monitoring the treatment effectiveness.

Natural waters (before treatment)
Turbidity: ≤ 5 NTU
NOM: ≤ 3 mgC/L TOC; ≤ 2 mgC/L DOC;
≤ 2 L/(mg.m) SUVA
Aerobic endospores: ≤ 40 ufC/100 mL

Spiked waters (before treatment)
Natural waters (on the left) spiked with
8.8-17.5 ug/L PhCs-total, 10-19 pharmaceuticals
1.3-11 ug/L pesticides-total, 10 pesticides
1.3 ug/L microcystin-LR

PAC/ceramic MF water quality results
- 0.01-0.03 NTU turbidity, regardless of the intake water quality and PAC dose (2-18 mg/L)
- No problems of PAC fines in the treated water, though using a 15 μm avg. diameter PAC.
- Aluminium residuals < 46 μg/L using in-line coagulation, i.e. PAC/alum/ceramic MF.
- Improvement of NOM removal, from 2-20% TOC removal with MF to 20-50% TOC, DOC, UV254nm removal using PAC/MF or PAC/alum/MF, higher removals with the latter.
- Total removal of aerobic endospores, used as indicators of protozoan (oo)cysts removal
- PAC/MF was not a complete barrier against bacteriophages, used as indicators of viruses, but it did improve their removal, from 4-6 PFU/100 mL to 0-1 PFU/100 mL.
- Removal of 83% to ≥ 98% total-pharmaceuticals, 78% to 98% total-pesticides and > 85% microcystin-LR using 2-18 mg/L PAC.
- Individually, the microcontaminants presented different amenability to PAC/MF removal and were classified in three groups. The main difference between groups was the removal reliability when low PAC doses were used (< 7 mg/L), which determined high competition scenarios between microcontaminants and NOM.
When should PAC/MF be considered a candidate treatment?

... for upgrading a conventional WTP...

In WTPs, it is important to:
- Assess the risks related with emerging contaminants
- If necessary, improve current barriers in conventional WTPs and/or
- Upgrade with advanced treatment technologies
- Promote multiple and physical barriers (to minimize the formation of oxidation by-products of unknown toxicity)

PAC/ceramic MF is a good option for upgrading conventional treatment for controlling dissolved micropollutants, including emerging contaminants.

Even optimized, the conventional drinking water treatment presents some limitations for controlling microorganisms resistant to chemical oxidation and dissolved microcontaminants, such as pharmaceuticals, pesticides and cyanotoxins.

The hybrid PAC/ceramic MF process is a good physical barrier for upgrading the conventional water treatment plants. PAC/MF implementation is very advantageous in terms of treatment effectiveness and reliability and therefore of water safety and will be more important as the lower the water quality and the lesser the alternative water sources are in a specific region, the higher are the risks associated with these challenging contaminants.

Relatively to PAC conventional application, the use of a ceramic MF membrane to retain PAC particles allows higher and more reliable disinfection capacity and the use of smaller PAC particles, with faster adsorption kinetics and therefore better performance, but still with very efficient separation even for PAC fines.

The benchmarking of conventional (PAC/CFS) and advanced (PAC/MF) technologies was one of LIFE Hymemb objectives. PAC/MF was able to achieve 20% higher removal of dissolved microcontaminants using similar PAC doses, with much lower residuals of turbidity, aluminium, total organic carbon and aerobic endospores, thus presenting higher efficacy and reliability.

Higher PAC doses and contact times could enhance the PAC/CFS removals, but attention must be paid to the fact that PAC dosing interfered with turbidity (due to PAC fines), requiring a safe barrier(s) downstream.
... in alternative to chemical processes...

PAC/MF is a physical barrier, therefore presenting advantages over chemical oxidation processes, which depend on several conditions of difficult simultaneous control, namely the oxidant dose and residual, the contact time and the water quality, particularly the NOM content, pH, alkalinity and temperature. The formation of oxidation by-products of unknown toxicity is a concern, particularly when the application of sufficiently high oxidant doses are restricted (water with high formation potential of THMs and bromide).

... and other membrane processes.

The hybrid PAC/ceramic MF technology allows a low-pressure membrane process to remove dissolved microcontaminants, as an alternative to tighter and more energy-consuming membrane technologies, such as nanofiltration (NF) or reverse osmosis (RO). Besides the lower energy consumption, compared with those technologies, PAC/ceramic MF is more flexible in process and operation, allowing MF to be changed to PAC/MF when necessary, operation in dead-end and/or cross-flow modes (often dead-end, with benefits in terms of energy demand and water recovery), easier membrane cleaning given the high tolerance to chlorine and the backwash feasibility.

Summing-up...

**WHEN** should PAC/MF be considered a candidate treatment?

- **Depending on the target contaminants**
  Pharmaceuticals and pesticides were classified in three groups based on the amenability to be removed by PAC/MF.

- **For upgrading a conventional WTP or in alternative to chemical processes and other membrane processes**
  PAC/MF was able to achieve 20% higher removals of dissolved microcontaminants than PAC/CFS using similar PAC doses, with much lower residuals of turbidity, aluminium, total organic carbon and aerobic endospores, therefore presenting higher efficacy and reliability.
PAC/MF, WHERE?

Depending on the intake water quality, which determines the membrane fouling potential...

For membrane application, a major obstacle is always the potential for membrane fouling, which requires the need for increasing the applied pressure in order to maintain a constant flux.

Membrane fouling can mainly occur by adsorption of solutes or particles onto the membrane, by membrane pore blockage, attributed to large particles, by deposition of the solutes or particles on the membrane surface, by gel formation in the openings of the pores, attributed mainly to macromolecules, by precipitation (scaling), attributed to salts, oxides and hydroxides and by the growth of bacteria on the membrane surface (biofouling).

A sustainable membrane operation therefore often requires pretreatment to reduce the membrane fouling agents in the water to be treated, i.e. particles, inorganic scaling agents, organic matter and/or bacteria.

Usual pretreatment for PAC/ceramic MF includes one or several of the following treatment steps:

- Coarse strainer, for removing large particles;
- Clarification by sedimentation or dissolved air flotation, for removing cyanobacterial cells and light/fine particles;
- In-line coagulation, for coagulating high molar mass hydrophobic NOM;
- Ozone, intended for pre-disinfection and NOM character change.

and the key water quality criteria may be summarized as:

<table>
<thead>
<tr>
<th>Key factors</th>
<th>Key water quality criteria for PAC/ceramic MF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity and algae</td>
<td>• The flux decline caused by the accumulation of particles and colloids on the membrane surface is largely reversible by backwash with water/air, but small particles and colloids smaller than the membrane pore size may be trapped within the pores and may not be easily removed.</td>
</tr>
<tr>
<td>Fe, Mn, hardness</td>
<td>• Interactions between ions, particularly multivalent ions (e.g. Ca\textsuperscript{2+}, Mg\textsuperscript{2+}, Mn\textsuperscript{2+} and Fe\textsuperscript{3+}), and NOM may promote the NOM fouling behaviour; there is the possibility that multivalent metals may promote PAC cake fouling.</td>
</tr>
<tr>
<td>NOM</td>
<td>• Water with high levels of iron, manganese and hardness should be site-tested for membrane fouling.</td>
</tr>
<tr>
<td>NOM</td>
<td>• Waters with high levels of iron and manganese may require pretreatment (e.g. oxidation, CFS and rapid sand filtration).</td>
</tr>
<tr>
<td>NOM</td>
<td>• Organic membrane fouling may be intense with waters presenting a high NOM content; a heavy deposition of organic matter on membrane surface may enhance PAC deposition and increase cake fouling.</td>
</tr>
<tr>
<td>NOM</td>
<td>• DOC is not adequate as the sole indicator of organic fouling, as NOM characteristics, such as hydrophobicity, size and functional groups are also important.</td>
</tr>
<tr>
<td>NOM</td>
<td>• As a general rule, PAC/MF requires, at least, upstream in-line coagulation. Site-testing should be performed.</td>
</tr>
</tbody>
</table>
... PAC/MF technology can complement a conventional WTP...

For WTP upgrade, PAC/MF technology can be used downstream the pre-oxidation (with low ozone doses)/conventional CFS/sand filtration treatment (which is the most common treatment sequence in Portugal, see WHEN), i.e. be used for disinfection and polishing, the latter including an enhanced control of microcontaminants, such as pharmaceutical compounds (option 1).

...or replace one or several sequence steps.

PAC/MF can also replace one, e.g. filtration (option 2), or several treatment steps, e.g. CFS clarification/filtration (option 3). With waters presenting a very low membrane fouling potential, the PAC/MF technology can even replace all conventional sequence line (option 4).

In all cases, in regions where the temperature is (seasonally or throughout the year) amenable to bacterial regrowth (such as in temperate regions like Portugal), a final chlorination is needed for ensuring a disinfectant residual to prevent the biofilm development in the water supply systems.
The unit operations/processes upstream the PAC/ceramic MF should depend on the raw water quality and potential for membrane fouling, treatment objective and economic considerations.

Options 1 and 2 – If PAC/MF technology is used for disinfection and polishing, there will be operational advantages, as lower membrane fouling risk, higher fluxes and filtration time, but the sludge production and chemical consumption in conventional clarification step (CFS) will not be reduced.

Options 3 and 4 – If PAC/MF replaces the conventional clarification steps (CFS and filtration) and/or the pre-oxidation with ozone, there will be savings in the chemicals’ consumption, lower sludge production and similar energy consumption for a safer production of high quality water.

In LIFE Hymemb demonstration in a Portuguese WTP, PAC/MF was tested with raw, ozonated, decanted and filtered waters – these were all low turbidity waters (≤5 NTU), with low and hydrophilic organic content (≤3 mg/L TOC, ≤2 L/(mg.m)). With the waters tested, direct PAC/MF was feasible with in-line coagulation and high fluxes (150-283 L/(m².h)) @ 0.6-0.8 bar, filtration time (≥2 hours), water recovery (≥97%) and treatment capacity (4.6-9.5 m³/(m².dia.bar)) were obtained. CEB per day, chemicals’ consumption, sludge production and energy consumption in PAC/MF are also summarized below.

<table>
<thead>
<tr>
<th>Water</th>
<th>Water quality turbidity</th>
<th>Alum mg/L Al₂O₃</th>
<th>Flux L/(m².h)</th>
<th>TMP bar</th>
<th>Filtration time h</th>
<th>CEB No./d</th>
<th>Water Recov. %</th>
<th>Treatment capacity m³/(m².dia.bar)</th>
<th>Chem. cons. kg/m³</th>
<th>Sludge prod. kg/m³</th>
<th>Energy cons. kWh/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw water</td>
<td>1.6 - 3 NTU 1.5 - 2.5 mg/L/C/L &lt; 2 L/(mg C.m)</td>
<td>PAC alum MF</td>
<td>3</td>
<td>150</td>
<td>0.6</td>
<td>2</td>
<td>97</td>
<td>4.9</td>
<td>0.068</td>
<td>36</td>
<td>0.046</td>
</tr>
<tr>
<td>Ozonized water</td>
<td>1.7 - 5 NTU 1.5 - 2.9 mg/L/C/L &lt; 1.1 L/(mg C.m)</td>
<td>PAC alum MF</td>
<td>3</td>
<td>173</td>
<td>0.8</td>
<td>2</td>
<td>1</td>
<td>97</td>
<td>4.8</td>
<td>0.068</td>
<td>36</td>
</tr>
<tr>
<td>Decanted water</td>
<td>0.4-1.7 NTU 1.2 - 2.0 mg/L/C/L &lt; 1.3 L/(mg C.m)</td>
<td>PAC MF</td>
<td>-</td>
<td>173</td>
<td>0.7</td>
<td>2 – 3</td>
<td>≤97</td>
<td>5.6</td>
<td>0.024</td>
<td>36</td>
<td>0.048</td>
</tr>
<tr>
<td>Filtered water</td>
<td>&lt; 0.1 - 0.2 NTU 1.3 - 2.6 mg/L/C/L &lt; 1 L/(mg C.m)</td>
<td>PAC MF</td>
<td>-</td>
<td>213</td>
<td>0.6</td>
<td>≥3</td>
<td>0.75</td>
<td>≥99</td>
<td>6.4</td>
<td>0.019</td>
<td>16</td>
</tr>
</tbody>
</table>

The microfiltration of raw water and ozonated water with no in-line coagulation presented high fouling rate between filtration cycles (7.8 ± 5.6 mbar/h) and a low productivity (flux of 87 L/(m².h)). The in-line coagulation (with 2-3 mg/L Al₂O₃) prior to the ceramic MF approximately half-reduced the fouling rate during the filtration cycles and to one sixth the fouling rate not recovered with backwashing. In-line coagulation also proved to be beneficial for PAC/ceramic MF. Therefore, in-line coagulation with alum (Al₂(SO₄)₃ xH₂O) proved to be an effective pre-treatment for ceramic MF and PAC/ceramic MF. Direct MF filtration achieved a TOC removal of 20%, increased to around 30% with alum/MF (3.1 mg/L Al₂O₃) and to 42-46% when PAC was combined (7-13 mg/L).
In-line coagulation with ferric chloride also proved to be an effective pretreatment for secondary effluent filtration by ceramic MF in TRUST project (Viegas et al. 2015). Taking into account the operating and water quality results and the economic analysis, it was concluded that PAC/MF technology should be considered as an alternative to the whole conventional treatment train, with upstream in-line alum coagulation, or as a post-treatment of the filtered water, in both cases with a final chlorination to ensure the chlorine residual in the water distribution systems.

**Summing-up...**

**PAC/MF, WHERE?**

- Depending on the intake water, which determines the membrane fouling potential
  - The key water quality criteria are turbidity and algae, Fe, Mn hardness and NOM concentration and nature.

- PAC/MF technology can complement a conventional WTP or replace one or several sequence steps
  - In LIFE Hymemb demonstration in a Portuguese WTP, PAC/MF was tested with raw, ozonated, decanted and filtered waters.
  - For these low turbidity, low and hydrophilic organic content waters (≤ 5 NTU, ≤ 3 mg/L TOC, ≤ 2 L/(mg.m)), direct PAC/MF was feasible with in-line coagulation.
PAC/MF, HOW?

How should PAC/MF be designed and operated?

Designing PAC/MF...

Scale and type of operation

PAC/MF process can be operated at any scale and in batch or in continuous mode, in dead-end or in cross-flow mode and with pre-treatment option (coagulant addition). When ceramic MF membranes are used, the most common configuration is continuous operation in dead-end mode.

![Schematic diagram of a common PAC/ceramic MF process](image)

Key components

The key components of a PAC/ceramic MF process are listed below.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane(s)</td>
<td>Ceramic, TiO$_2$-Al$_2$O$_3$</td>
</tr>
<tr>
<td>Size</td>
<td>Typically 1.2 m long, 25 mm diameter</td>
</tr>
<tr>
<td>Configuration</td>
<td>Multichannel</td>
</tr>
<tr>
<td>Area</td>
<td>0.16 – 0.45 m$^2$</td>
</tr>
<tr>
<td>Cut-off</td>
<td>0.1 – 0.45 $\mu$m</td>
</tr>
<tr>
<td>Bursting Pressure</td>
<td>80 bar</td>
</tr>
<tr>
<td>pH resistance</td>
<td>0 – 14</td>
</tr>
</tbody>
</table>
### Key design parameters and variables

The key parameter when designing a membrane plant is the flux. Other parameters that must be considered include the specific flux, the transmembrane pressure, the membrane fouling and fouling rate, the filtration time, the backwash frequency, the CEB frequency, the plant downtime, the feed flow rate, the PAC dosing and the energy requirements — see Terms and definitions. Their discussion is presented below.

- **Flux and normalized flux**

Flux is one of the main parameters determining the economic feasibility of the membrane process and is the key factor, together with the design capacity, that defines the size of the membrane plant.

Flux (J, L/(m²·h) or lmh) is defined as the permeate (or filtrate) flow rate (Qₚ, L/h) per unit of membrane filtration area (Aₘ, m²). Since water temperature may have a significant impact on flux, flux is usually presented at 20°C, chosen as a reference temperature, and is designated J₂₀. J is converted to J₂₀ by applying a temperature correction factor (TCF, dimensionless) which is defined as the ratio of the water viscosity at temperature T to the viscosity at 20°C:

\[
J_{20} = \frac{Q_p}{A_m} \cdot TCF
\]

The flux should be maximised as to minimise the membrane area requirements. However, higher fluxes imply higher operating pressures.
• **Specific flux**

To assess membrane performance a useful concept is the specific flux ($M_{20}$, L/(m².h.bar)) resulting from normalising the flux for pressure:

$$M_{20} = \frac{J_{20}}{\text{TMP}}$$

$M_{20}$ allows relating the flux with the transmembrane pressure (TMP) and is constant and maximum for low fluxes but, due to membrane fouling, slowly decreases for higher fluxes and steeply decreases above what could be termed as sustainable flux.

Thus, although increasing the flux decreases the membrane area requirements it increases the operating pressure and might imply more frequent membrane cleaning, directly impacting the energy requirements (higher), water recovery (lower), consumption of reagents (higher) and plant downtime (higher).

• **Transmembrane pressure (TMP)**

The transmembrane pressure (TMP, bar) is defined as the pressure gradient across the membrane and is the driving force for the water transport across a microporous membrane, such as MF and UF. The TMP is defined by the pressure on the feed side of the membrane (represented by the average of the feed inlet ($P_{\text{feed in}}$) and outlet ($P_{\text{feed out}}$) pressures) minus the permeate pressure:

$$\text{TMP} = \frac{(P_{\text{feed in}} + P_{\text{feed out}})}{2} - P_{\text{permeate}}$$

When operating at constant flux an increase in hydraulic resistance occurs due to membrane fouling, which is expressed as a TMP increase along a filtration cycle, thus increasing the energy required to achieve filtration.

• **Fouling and fouling rate**

Membrane fouling can mainly occur by adsorption of solutes or particles to the membrane, by membrane pore blockage, attributed to large particles, by deposition of the solutes or particles on the membrane surface, by gel formation in the openings of the pores, attributed mainly to macromolecules, by precipitation (scaling), attributed to salts, oxides and hydroxides and by the growth of bacteria on the membrane surface (biofouling).

Based on the attachment strength of the solutes or particles to the membrane, fouling can be divided into reversible fouling and irreversible fouling. Reversible fouling can be removed by either backwash or CEB; irreversible fouling cannot be removed through either backwash or CEB and requires the need for a clean-in-place (CIP) procedure for membrane recovery.

The fouling rate is defined as the TMP variation over time. It can be calculated for a filtration cycle (FRw), between filtration cycles, thus taking into account the backwash (FRb), or between sets of filtration cycles with a CEB in between (FRc). The ratio FRb/FRw allows assessing the backwash efficiency in fouling mitigation (backwash efficiency = 1 - FRb/FRw) and the ratio FRc/FRb allows assessing the CEB efficiency in fouling mitigation (CEB efficiency = 1 - FRc/FRb).
Fouling determines the duration of a filtration cycle and the backwash and CEB frequencies.

- **Filtration time (and backwash frequency)**
  
  The filtration time is the duration of a filtration cycle between two backwashes or a backwash and a CEB. It defines the backwash frequency, i.e. once per filtration time. It is one of the most important optimisation parameters and should be as long as possible, to minimise plant downtime and water consumption, without compromising the membrane performance.

- **CEB frequency**
  
  The CEB frequency is a major optimisation parameter as it affects the TMP and the fouling rate. It should be conducted as less frequently as possible, as it consumes water and reagents and implies plant downtime, without compromising the membrane performance.

- **Plant downtime**
  
  The plant downtime (min/day) includes the time spent in membrane cleaning procedures (membranes backwash, CEB and CIP operations) and should consider the time spent in maintenance procedures and in membrane integrity testing. The feed flow rate has to compensate the plant downtime.

- **Feed flow rate**
  
  The feed flow rate \( Q_f \) (L/h) is the feed flow rate needed to deliver the plant capacity \( Q_p \) (L/h).

  \[
  Q_f = \frac{A_m \cdot J}{1 - \frac{plant \ downtime}{24 \cdot 60}}
  \]

- **PAC dosing conditions**
  
  The PAC dosing conditions determine the removal efficiencies of the target contaminants. The key parameters are the dose, the contact time \( t_c \) (h) and the velocity gradient \( G \) (s\(^{-1}\)) for mixing. To achieve contaminants efficient adsorption a long contact time (> 30 min) and a sufficient mixing velocity gradient (≥ 120 s\(^{-1}\)) should be provided. PAC should not be applied near the point of chlorine or other oxidant application.

- **Power requirements**
  
  The power requirements of the PAC/MF process are associated to pumping and to PAC mixing. Regarding pumping, power is required for pressurising the feed stream, for backwashing, for performing the CEB and for reagents (PAC and eventually coagulant) dosing\(^1\). The feed and recirculation pumps and the PAC mixer are the most power demanding (and are in the same order of magnitude):

\(^1\) High-pressure membrane processes and low-pressure polymeric membrane processes are operated in cross-flow mode requiring a feed recirculation pump, also a major power demanding pump. This energy parcel does not exist in dead-end ceramic MF.
Technical Guidelines of PAC/MF for Drinking Water Production

\[
Power_f = \frac{P_{\text{feed}} Q_f}{\eta} \left(1 - \frac{\text{plant downtime}}{24 \cdot 60}\right) \cdot \frac{1}{3600}
\]

\[
Power_{\text{mix}} = \frac{1.008 \times 10^{-9} \cdot G^2 \cdot t_c}{\eta}
\]

where \(\eta\) is the motor efficiency.

The \textbf{unit energy consumption} (often expressed in kWh/m\(^3\)) is obtained by dividing the total power requirements by the permeate flow rate.

**Operating PAC/MF...**

Besides the key parameters and variables previously discussed, for assessing PAC/MF operational performance the water recovery rate and the treatment capacity could be used as indicators, the higher the values the better the performance.

- **Water recovery rate**

The water recovery rate (or water recovery or recovery) is defined as the amount of feed water that is converted into product water, expressed as a percentage.

\[
R = \frac{V_p - V_{bw} - V_{cc}}{Q_f \times t_{\text{filt}}}
\]

As the definition of recovery is not consensual throughout the water treatment industry it is important to stress that in this document the water recovery takes into account the use of permeate water for membrane cleaning purposes, such as backwashes \((V_{bw})\) and CEBs \((V_{CEB})\), and the plant downtime during these procedures.

- **Treatment capacity**

Treatment capacity \((m^3/(m^2 \cdot \text{day} \cdot \text{bar}))\) is the effective amount of filtered water that can be produced from a membrane module over a time-period, membrane area \((A_m)\) and intake pressure \((P_{\text{feed}})\). It assesses the quantity of water available for its intended use and, therefore, it deducts the volume of permeate water used in backwash and CEBs and takes into account the productive time that a unit is off-line for cleaning procedures. It includes the energy demand for the filtration.

\[
\text{Treatment capacity} = \frac{V_p - V_{bw} - V_{cc}}{(t_{\text{filt}} + t_{bw} + t_{CEB}) \times A_m \times P_{\text{feed}}}
\]

The treatment capacity integrates most state-variables of MF performance: flux, applied pressure, fouling, filtration time and membrane cleaning. Therefore, there is no need for other indicators.
Recommended ranges of operation of key parameters and variables

The recommended ranges of operation of the key parameters and variables presented below were derived during LIFE Hymemb demonstration for a low turbidity intake water (≤ 5 NTU, ≤ 3 mg/L TOC, ≤ 2 L/mg-m SUVA) and reflect a technical and economic analysis (the latter presented in Economic Analysis).

<table>
<thead>
<tr>
<th>Key parameter and variable</th>
<th>Recommended range of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flux (normalised) ( J_{\text{20}} ) (L/(m(^2).h))</td>
<td>150 – 280</td>
</tr>
<tr>
<td>Inlet pressure (bar)</td>
<td>0.6 – 0.9</td>
</tr>
<tr>
<td>TMP (bar)</td>
<td>0.6 – 0.8</td>
</tr>
<tr>
<td>Filtration time (h)</td>
<td>2 – 3</td>
</tr>
<tr>
<td>Backwash frequency (N./d)</td>
<td>8 – 12</td>
</tr>
<tr>
<td>flux (L/(m(^2).h))</td>
<td>500</td>
</tr>
<tr>
<td>pressure (bar)</td>
<td>ca. 1.5 (water backwash)</td>
</tr>
<tr>
<td>CEB water volume spent (L/m(^3))</td>
<td>&lt; 15</td>
</tr>
<tr>
<td>cleaning agents</td>
<td>sodium hypochlorite (≤ 1000 mg/L Cl(_2) in membrane)</td>
</tr>
<tr>
<td>sulphuric acid (pH 1-2 in membrane)</td>
<td></td>
</tr>
<tr>
<td>soaking time (min)</td>
<td>15-30</td>
</tr>
<tr>
<td>total frequency (N./d)</td>
<td>( \frac{3}{4} – 1 )</td>
</tr>
<tr>
<td>sodium hypochlorite freq. (N./d)</td>
<td>( \frac{3}{4} – \frac{1}{2} )</td>
</tr>
<tr>
<td>acid frequency (N./d)</td>
<td>( \frac{3}{4} – \frac{1}{2} )</td>
</tr>
<tr>
<td>Specific flux (L/(m(^2).h.bar))</td>
<td>200 – 500</td>
</tr>
<tr>
<td>Water recovery rate (%)</td>
<td>97 – 99</td>
</tr>
<tr>
<td>Treatment capacity (m(^3)/(m(^2).d.bar))</td>
<td>5 – 10</td>
</tr>
<tr>
<td>Fouling rate</td>
<td></td>
</tr>
<tr>
<td>within cycles (FRw, mbar/h)</td>
<td>0 – 15</td>
</tr>
<tr>
<td>between cycles (FRb, mbar/h)</td>
<td>0 – 5</td>
</tr>
<tr>
<td>with CEB (FRc, mbar/d)</td>
<td>0 – 5</td>
</tr>
<tr>
<td>backwash efficiency (%)</td>
<td>50 – 80</td>
</tr>
<tr>
<td>CEB efficiency (%)</td>
<td>95 – 100</td>
</tr>
<tr>
<td>PAC size (μm)</td>
<td>6 – 15</td>
</tr>
<tr>
<td>pH(_{\text{pzc}})</td>
<td>depends on the contaminants targeted, usually alkaline PACs are more efficient for negatively charged contaminants</td>
</tr>
<tr>
<td>specific area (( S_{\text{BET}} )) (m(^2)/g)</td>
<td>the higher the better, often &gt; 1000 m(^2)/g</td>
</tr>
<tr>
<td>porous structure</td>
<td>micropores host the preferential adsorption sites for low molar mass contaminants; mesopores are important for adsorbing intermediate molar mass contaminants and for compounds less amenable to adsorption under strong competition conditions, i.e. low PAC doses and/or high(er) competitors’ concentration (other microcontaminants and water background NOM); good results were obtained with 50/50 of microporous/mesoporous volume and total per volume &gt; 0.7 cm(^3)/g</td>
</tr>
</tbody>
</table>
Key parameter and variable | Recommended range of operation
--- | ---
PAC suspension concentration (slurry) | ≤ 2 g/L (recommended), agglomerates formation should be avoided
Contact time (min) | ≥ 30
Mixing velocity gradient (G) (s⁻¹) | 120
PAC dose (mg/L) | depends on the target contaminants
total removal by MF, no need for PAC addition
Chemically resistant biological forms protozoan (oo)cysts | 10
NOM and oxidation by-products good and reliable removal (DOC < 1.6 mg/L) | depends on the target contaminants, indicative ranges below should be validated case-by-case
Low molar mass microcontaminants | for 75% average removal
| 2
| for 85% average removal
| 5
| for 90% average removal
| 10
PAC/MF coagulant (Al₂O₃) dose (mg/L) | 3
(for non coagulated waters)
PAC/MF unit energy consumption (kWh/m³) | 0.05
PAC/MF chemicals consumption (kg/m³) | non-coagulated intake waters: 0.07
coaagulated intake waters: 0.02
PAC/MF sludge production (kg/m³) | non-filtered intake waters: 36 – 41
filtered intake waters: 16 – 21

Summing-up...

How should PAC/MF be designed and operated?

- **Designing PAC/MF**
  Key design parameters and variables were discussed for guiding the PAC/MF design.

- **Operating PAC/MF**
  Recommended ranges of operation of key parameters and variables were derived during LIFE Hymemb project demonstration for low turbidity intake water.
Technical Guidelines of PAC/MF for Drinking Water Production

Economic Analysis

Assumptions

The following assumptions were made for developing the cost functions:

- The plant lifespan was assumed to be 40 years (typical values);
- The plant is assumed to operate 24 hours per day, 365 days per year;
- The plant is to be offline for backwashing (values obtained from the LIFE Hymemb prototype demonstration), CEB (values obtained from the prototype demonstration), integrity testing (standard values – 20 minutes for the test, performed once a week), and routine maintenance (standard values – 18 minutes per day);
- During normal operation time, additional product water is generated and stored to be used during backwashing and CEB cycles;
- The capital expenditure costs (CAPEX) considered the initial acquisition of the following components, with the indicated lifespan:
  - Membranes – 20 years;
  - Pipes and valves – 20 years;
  - Instrumentation and controls – 8 years;
  - Tanks and frames – 14 years;
  - CEB chemical agents skid – 15 years;
  - Feed, backwash and PAC dosing pumps – 10 years;
  - Miscellaneous equipment, which included electrical supply and distribution equipment, disinfection facilities, treated water storage and pumping, the building that houses the equipment and the wash water recovery system – 14 years.
- The operating expenditure costs (OPEX) considered:
  - The annualised costs of replacement of equipment;
  - The energy cost for pumping and mixing (0.08 €/kWh – cost provided by the water utility (Águas do Algarve));
  - The personnel costs (considering an annual cost of 20 k€/worker – average value of Portuguese WTPs – and assuming an allocation of 50% of the personnel of a conventional WTP);
  - The chemical reagents’ costs (PAC: 2.44 €/kg (supplier data); Coagulant: 0.165 €/kg; Sodium hypochlorite solution: 0.416 €/kg; Sulphuric acid solution: 0.130 €/kg – all costs provided by the water utility);
  - Maintenance costs (1.5% of the total capital costs).
- The annual interest rate considered was 3.2% (average financing rate of Águas de Portugal group between 2013 and 2015).
The cost functions of the components of the PAC/MF process in the tables below were adapted from the literature or provided by suppliers. They are all power-type functions of the form:

\[ \text{Cost} = a \cdot \text{variable}^b \]

<table>
<thead>
<tr>
<th>Input cost</th>
<th>Variables and parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membranes cost (€)(^2)</td>
<td>variable: membrane area (m(^2))</td>
</tr>
<tr>
<td></td>
<td>(a = 756; b = 0.97)</td>
</tr>
<tr>
<td>Pipes and valves cost (€)(^3)</td>
<td>variable: membrane area (m(^2))</td>
</tr>
<tr>
<td></td>
<td>(a = 5313; b = 0.42)</td>
</tr>
<tr>
<td>Instruments and controls (€)(^2)</td>
<td>variable: membrane area (m(^2))</td>
</tr>
<tr>
<td></td>
<td>(a = 1296; b = 0.66)</td>
</tr>
<tr>
<td>Tanks and frames (€)(^2)</td>
<td>variable: membrane area (m(^2))</td>
</tr>
<tr>
<td></td>
<td>(a = 2732; b = 0.53)</td>
</tr>
<tr>
<td>Miscellaneous (€)(^2)</td>
<td>variable: membrane area (m(^2))</td>
</tr>
<tr>
<td></td>
<td>(a = 7052; b = 0.57)</td>
</tr>
<tr>
<td>Pumps (€)(^4)</td>
<td>variable: power (kW) \times\text{ safety factor (}=2)</td>
</tr>
<tr>
<td></td>
<td>(a = 26011; b = 0.354)</td>
</tr>
</tbody>
</table>

**PAC/MF costs**

The output costs shown below were developed for the conditions demonstrated within the LIFE Hymemb project. For each intake water, the total production cost (€/m\(^3\)) and the OPEX and investment costs are plotted as functions of the plant flow rate, for the standalone MF and for the PAC/MF process, while the cost structure, breakdown in capital, replacement of components, reagents, energy, maintenance and personnel, is plotted for the median of Alcantarilha WTP (90 000 m\(^3\)/d). In the total production cost graphs the solid lines represent the MF standalone process and the dotted lines represent the PAC dosing cost, which includes the reagent, the required pump(s) and the mixing and pumping energy. A PAC dosing of 10 mg/L was assumed.

---

\(^2\) Provided by the supplier (ORM - Tecnologia e Ciência na Indústria Lda.) on September 2016  
\(^3\) Adapted from: Guerra and Pellegrino (2012)  
\(^4\) Adapted from: Ramos et al. (2015)
Technical Guidelines of PAC/MF for Drinking Water Production

Output costs

**PAC/ceramic MF intake = Filtered water** (≤ 0.1 - 0.2 NTU, 1.3 - 2.6 mg C/L, < 1 L/m.mg C)

![Graph showing total production cost (€/m³) vs. plant flow rate (m³/d)]

---

**PAC/ceramic MF intake = Raw water** (1.6 - 3 NTU, 1.5 - 2.5 mg C/L, < 2 L/m.mg C)

![Graph showing total production cost (€/m³) vs. plant flow rate (m³/d)]
Replicability and transferability

These guidelines were derived for controlling by PAC/ceramic MF a wide range of contaminants, from aerobic endospores to natural organic matter, microcystins, pesticides and pharmaceutical compounds (22 of these emerging contaminants) in drinking water production.

However, due to its flexibility, PAC/MF technology can be easily replicated, i.e. used in different drinking water treatment plants for the same or other target contaminants, or transferred, i.e. be used for different purposes, e.g. for wastewater treatment and/or water reclamation aiming at safe discharge or safe unrestricted water reuse.

In order to improve its replicability and transferability potential, these guidelines were comprehensively developed with terms and definitions, process fundamentals, answers to when, where and how using the technology and how to design and estimate the costs involved. The objective was to facilitate and assist the use of this knowledge and information for the application of PAC, ceramic MF or PAC/MF for other contaminants than those targeted by LIFE Hymemb, e.g. other pharmaceutical compounds, as well as for other applications.

Data and information derived for other applications in earlier or ongoing projects are consistent with the information herein contained and may be found in Further reading. This includes the application of coagulation/ceramic MF or UF and PAC/coagulation/ceramic MF for treating secondary effluent aiming at unrestricted urban water reuse (work developed within TRUST FP7 project; Viegas et al. 2015), PAC/polymeric UF for pharmaceutical and personal care products removal from wastewaters (Rodriguez et al. 2016), PAC/polymeric low-pressure NF for controlling pharmaceutical compounds in reclaimed water (work developed within aWARE LIFE11 ENV/ES/000606 project; Viegas et al. 2017) and PAC/coagulation for improving the current barriers for controlling pharmaceutical compounds in urban wastewater treatment plants (ongoing work in LIFE Impetus LIFE14 ENV/PT/000739; Rosa et al. 2017).
Further reading

The results from the field demonstration are to be published in scientific papers under preparation and further editions of these guidelines are foreseen. Updated news may be found in www.life-hymemb.eu.


TITLE: Tailoring hybrid membrane processes for sustainable drinking water production

REFERENCE: LIFE12 ENV/PT/001154

COORDINATING BENEFICIARY: LNEC, I.P.

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TOTAL BUDGET: 631 k€

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