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The challenge of zero discharge: from water balance to regeneration

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Abstract

Wastewater treatment is traditionally considered a separate part of an industrial activity, hardly connected to the production units themselves. Scarcity of water and energy, and legal requirements for discharge of waste and wastewater will force the industry to change this approach to a more integrated concept of connecting the residual output (in terms of waste, wastewater and energy loss) to the input (in terms of materials and energy). This paper explores the possibility of using a process cycle where wastewater treatment is intended for water recycling, taking into account the mass balance of materials other than water and the energy balance as well. Three consecutive steps in this approach will be discussed: (1) investigation of the current water balance; (2) optimization of the water consuming processes; and (3) development of an overall concept for the optimized processes, with a zero discharge or virtual zero discharge of water (and other materials), and a minimal consumption of energy. The first step requires full knowledge and control of all water consuming processes, including e.g., cleaning-in-place (CIP) operations, rinsing etc. This is a very complex task, as will be shown in a case study for a brewery in Flanders, Belgium. In the second step, processes are combined by reusing waste water of a process as incoming water for another process. Examples are cooling processes, tank cleaning and truck cleaning. The final step is the regeneration of wastewater so that it can be recycled to (one of) the processes. Membrane technology plays a key role in this step. As an example, a possible treatment scheme using membrane processes will be given for the water flows in a typical medium size brewery. This scheme includes ultrafiltration (UF) for removal of particles, fibres and suspended solids, and nanofiltration (NF) for the removal of salts and organic matter. The NF concentrate is to be treated separately in a dewatering step.

Keywords: Water recycling; Membrane processes; Water balance; Zero discharge; Industrial effluents; Brewery wastewater

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1. Introduction

The industry nowadays is faced with increasing problems of water supply, and increasing costs for waste water discharge. A systematic approach to water management helps to keep the water issue under control. This can be done by controlling water input, consumption and output, and by gearing all water-related activities to one another. At the input side, the emphasis is on searching alternative sources for process water (other than groundwater or tap water). Surface water, if available, can be an option for some companies; brackish water is a possible source on condition that an adequate pretreatment method is used. Wet countries might investigate the possibility of using rainwater, although this is usually only feasible when small quantities are needed in low-quality purposes, such as sanitary water. A further option is to regenerate waste water and recycle it as process water. Waste water often requires an extensive treatment before it can be discharged. Further purification in order to obtain a water quality fit for reuse is often a realistic option in terms of additional treatment cost versus the benefits of using recycled water [1]. Three advantages are to be taken into account: (1) recycled water is a supplementary and reliable source of fresh water, which can add to existing sources or replace them; (2) the net volume of water consumed decreases drastically; (3) the volume of wastewater to be discharged (and, consequently, also costs and taxes) decreases; permits are no longer impediments for the company's expansion.

This article presents a step-by-step method to optimize the water balance in a given company, in three steps. The first step is to investigate the current water balance in detail. This seems to be very straightforward, but usually leads to complex measurements and calculations. Informations of how much water is consumed in which processes allows to take simple measures to save water. The second step is to combine water consuming processes and reuse water where possible for other purposes requiring a lower water quality. Typical examples of possible candidates are cooling processes, tank cleaning and truck cleaning. The water pinch method offers a theoretical approach to do this; however, practical impediments often need to be tackled. The final step is to regenerate partial waste streams and re-introduce them into the process cycle. Because of the complexity of most wastewaters to be treated, this requires one or more membrane separations, often using pressure driven processes such as ultrafiltration (UF) and nanofiltration (NF).

2. Estimating the water balance

A water balance is a numerical account of how much water enters and leaves a plant, and where it is used within the plant. It should contain detailed information about the amount of water used by each process. The water balance is a crucial instrument to understand and manage water flows throughout the plant, to identify equipment with water-saving opportunities, and to detect leaks.

The set-up of a water balance requires a preliminary survey of existing data, an assessment of major gaps in the available information and a decision on how detailed the water balance should be. This leads to choices concerning the amount of work and the technical resources that have to be invested in the project.

A typical example is the water balance made for a medium size brewery in Belgium. In this plant, numerical data were missing to construct a water balance, and no formal knowledge on the organization and lay-out of the water distribution network within the company was available.

The main source of the brewery process water is well water. This water is brought from a depth of 60 m (175,000 m^3) and 360 m (45,000 m^3) at a constant temperature of 12°C. Its cost amounts to 0.075 €/m^3. At peak moments, more water is needed than the well water pumps can provide. Therefore, the company will supplement its water needs with tap water at 0.87 €/m^3. Before being used in the production process, the water is treated in order to obtain the quality which is needed for each specific application in the brewery:

- On arrival in the brewery, all water is first chlorinated, then stored in a reservoir (central water collector) with a capacity of 400 m^3.
- 80% of the stored water is directly used from this reservoir, without further treatment. This is the "cleaning water", also called "type I water". It is mainly used for CIP cleaning procedures, in the bottling plant and for cooling purposes.
- About 20% of the available water is demineralized. To this end, the water first passes an activated carbon column for dechlorination and removal of organic matter. Afterwards, the water is deionized by passage through anion- and cation columns. Thus, process water or deminwater "type II" is produced mainly for use in the brewing process, but also for steam generation and a few other technical applications.
- About 8 % of the deminwater is further treated by ultrafiltration, deaeration and UV-irradiation to obtain the sterile and ultraclean "correction water" or "type III water", which is mainly used to dilute the beer to the required alcohol concentration.

In order to obtain more detailed information on the individual water consuming processes, supply pipes were traced and schemes were drawn to understand groupings and connections of equipment in the water network. The organic growth of the brewery resulted in a rather chaotic lay-out of utilities such as water supply. In many cases, water is taken from existing pipes left from an earlier installation, or simply tapped from the water supply of a completely other facility. Thus, for constructing a rough internal water balance, existing water meters provided only partial information. Additional flow measurements were carried out for all subunits, including CIP stations, bottling plant, rinsing of bottles and crates, and non-continuous operations such as cleaning of tanks. It was found that on a weekly basis, only 3960 m^3 could be accounted for on a total influent volume of 5270 m^3, i.e. 25% of all incoming water is not accounted for. A loss in the water balance of more than 10% indicates that water consumption is not sufficiently under control [2].

No indications of important leaks or spills have been observed during measurements. Nonetheless, an important quantity of water (ca. 1300 m^3 per week) was "lost". On the basis of the water balance made here, a systematic study can be made of water flows as a function of time in the various water flows, to detect exceptional or occasional applications of water, or to record where water is consumed during periods when there should be none and, consequently, where possible leaks are located.

Wastewater quality varies significantly, depending on the type of beer produced and on the place where the wastewater is generated. In general, the organic load of wastewaters from facilities producing high fermentation beers is higher than for low fermentation beers; the same conclusions can be made on suspended solids. Furthermore, the highest organic load is found in wastewaters from rinsing of bottles and lager tanks; the lowest values are found in the final effluent (after biological treatment). This difference is illustrated by comparing two different types of wastewater. The first type is rinsing water used for the returned bottles, which contains small fractions of beer and non-dissolved fractions originating from labels, sand etc. The suspended solids concentration ranged from 60 to 100 mg/l; the ion conductivity from 950 to 1600 µS/cm; and the COD from 380 to 480 mg/l. The second type is rinsing water from the fermentation tanks, which contains large concentrations of non-settleable yeast particles with a size of approx. 10 µm. The suspended solids concentration ranges from 760 to 2300 mg/l (10–20 times higher than for the first type); the ion conductivity from 580 to 1100 µS/cm (slightly lower than for the first type); and the COD from 2800 to 8700 mg/l (10–20 times higher than for the first type).

3. Overall process optimization

Reusing wastewater streams as an input for less demanding installations is a second step towards a zero-discharge system. Reuse of wastewater is well documented in literature. Two theoretical approaches can be considered: Water Pinch techniques, which were derived from the concept of Energy Pinch for the optimalisation of heat exchanger networks; and Water Scan techniques, which provide a more intuitive approach. In order to apply these concepts, a water balance is essential. Both qualitative and quantitative requirements should be specified for each individual water input at an installation. As for the qualitative requirements, it is important that the minimum quality specifications for each water flow should be stated (even if in the present situation, each installation simply gets the best water quality available anyway).

The Water Pinch method implies the determination of the minimal water use by an installation, needed to evacuate contaminants from a process, given an initial contamination load. The combination of all these minimal water quantities, effluent characteristics and maximum allowed contamination loads for all processes in the plant then determines the overall minimal water use. This calculation is executed three times under different assumptions:

1. existing allowed contamination loads for water inputs are not changed. This results in few possibilities for water reuse, but relatively cheap solutions;
2. more effluents become available for reuse if allowed contamination loads for selected processes are relaxed;
3. all or selected effluents are treated (regenerated) before being used as an input. In this way, several effluents are theoretically eligible for reuse, but significant investments are required.

The analysis of the results also reveals which process is a bottleneck for further reducing water consumption in the plant. Improving the water use characteristics of this process will result in the most cost effective impact on the water use for the company as a whole [3].

The water pinch method is in many cases difficult to implement. It requires that effluents of installations are redirected, serving as an input for another process. New water treatment equipment may have to be added. Frequently, individual effluent streams have to be mixed together in order to obtain the required input characteristics. This typically has following implementations:

- extra piping, pumps, valves, etc. is required. Besides costs, this adds to the already overcrowded infrastructure and complexity in a plant;
- water consuming processes become linked to each other, even if they are functionally not related. New operational constraints are thus created on both processes;
- the water input for one installation may require a precise mixture of effluents. But in practice, hardly any process is operated 100% continuously, so that an influent with stable characteristics is not always possible.

More practical ‘common sense’ methods were developed to help reducing the water consumption in a production plant. These methods can be called Water Scan techniques; they are not based on a theoretical framework but all start from a water balance of the plant (as discussed above), upon which ideas are gathered on how to manage the water system more efficiently, concentrating on reducing costs. Good housekeeping and opportunities for simple direct reuse are main attention points at this stage. Application of new techniques for water treatment or investments in less water consuming technologies are considered. Opportunities for water saving practices are then classified based on their financial and technical consequences. Taking available resources into account, the most promising projects are chosen and a planning for their implementation is proposed.

During a Water Scan in a typical medium size Belgian brewery, three wastewater streams were selected for regeneration using nanofiltration: bottle rinsing water (similar to [4]), rinsing water from the brewing house, rinsing water from the tanks where the filtered beer is stored. Four NF membranes were used: UTC-20 and UTC-60 (Toray Ind. Inc., Japan), and Desal 5 DK and Desal 51 HL (Osmonics, USA). The results are given in Table 1 for the COD (Chemical Oxygen Demand), measured using standard methods [5], and in Table 2 for the total ion concentration, measured as conductivity.

The composition of the wastewater streams is time-dependent, as can be concluded from the variability of the feed streams in different samples (filtration with different membranes). From Table 1 it can be seen that the COD of the filtered rinsing water from the brewing house is sufficiently low for reuse. The filtered water is not to be used in the brewing house itself, because of the possible risk of contamination of the beer, but can be used as rinsing water for e.g. crates. The COD of the other filtrates is too high for reuse.

Table 2 shows that there is a partial removal of ions due to nanofiltration. For the rinsing water from the storage tanks for filtered beer, the residual conductivity is below the standard for drinking water (400 μS/cm). For the bottle rinsing water and the rinsing water from the brewing house, the conductivity is acceptable for the UTC-20 membrane. Thus, the rinsing water from the brewing house can be reused after filtration, on condition that a membrane is selected with sufficient ion rejection.

Table 1
COD (mg O_2/l) in selected wastewater streams before and after nanofiltration

	Bottle rinsing water		Rinsing water from brewing house		Rinsing water from storage filtered beer	
	Feed	Filtered (% rejected)	Feed	Filtered (% rejected)	Feed	Filtered (% rejected)
UTC-20	592	112 (81)	102	1 (99)	2636	136 (95)
UTC-60	844	210 (75)	78	24 (69)	3692	143 (96)
Desal 5 DK	1509	136 (91)	137	2 (98)	3612	144 (96)
Desal 51 HL	1370	97 (92)	102	12 (88)	2844	147 (95)

Table 2
Conductivity (μS/cm) in selected wastewater streams before and after nanofiltration

	Bottle rinsing water		Rinsing water from brewing house		Rinsing water from storage filtered beer	
	Feed	Filtered (% rejected)	Feed	Filtered (% rejected)	Feed	Filtered (% rejected)
UTC-20	3730	782 (79)	2020	535 (73)	1296	193 (85)
UTC-60	3530	1405 (60)	2440	929 (62)	1808	214 (88)
Desal 5 DK	5230	3320 (36)	3020	1818 (40)	1782	357 (80)
Desal 51 HL	4350	872 (80)	3020	1175 (61)	1377	146 (89)

4. Water regeneration using membrane processes

It is obvious that regeneration of partial wastewater streams only decreases the water volumes needed for the brewing activities, but a (virtual) zero discharge is not yet feasible. The reason for this is that wastewater treatment generates side streams such as sludge volumes, which would need to be reused as well in the strict sense of zero discharge. Furthermore, brewing is particular in the sense that materials are brought into contact with food (beer), which requires special safety regulations, especially in terms of microbiological safety. One must also be aware of the psychological barrier of using wastewater in food products. This is an impediment to zero discharge systems. Current improvements are more focused on partial water recovery. In order to achieve this, the remaining wastewater fraction needs to be regenerated up to a level similar than the freshwater currently used in the company. Fig. 1 is a possible treatment method for the end-of-pipe wastewater, i.e. all waste streams not internally regenerated, after biological treatment in an activated sludge system.

Nanofiltration of the biologically treated effluent was tested experimentally using four NF membranes (UTC-20 and UTC-60 (Toray Ind. Inc., Japan), and Desal 5 DK and Desal 51 HL (Osmonics, USA)). The results are given in Table 3 for the COD, and in Table 4 for the conductivity. Apart from these parameters, also other water parameters are important, in particular the microbiological composition of the water. It is assumed here that all micro-organisms are well rejected (and thus removed from the feed water), as is known for NF membranes.

Table 3 shows that the COD of the filtered permeate is low enough for reuse (not detectable for all cases). The conductivity of the permeate is also acceptable. Thus, the bio-effluent can be reused for all purposes where there is no contact

Table 3
COD (mg O_2/l) in bio-effluent before and after nanofiltration

	Bio-effluent	
	Feed	Filtered (% rejected)
UTC-20	72	< 5
UTC-60	23	< 5
Desal 5 DK	46	< 5
Desal 51 HL	43	< 5

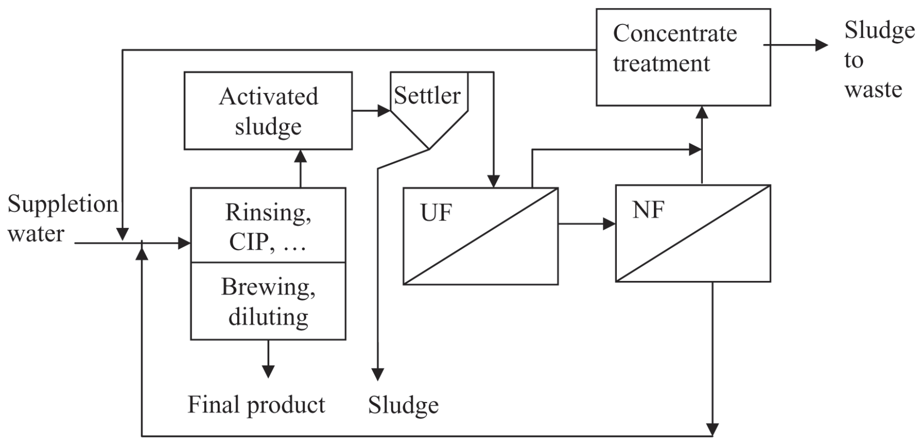

Fig. 1. Overview of a possible water cycle in a brewery.

Table 4
Conductivity (µS/cm) in bio-effluent before and after nanofiltration

	Bio-effluent	
	Feed	Filtered (% rejected)
UTC-20	2080	565 (73)
UTC-60	2040	544 (73)
Desal 5 DK	2060	537 (74)
Desal 51 HL	2120	817 (61)

with the beer (or, with materials in contact with the beer such as bottles and kegs).

By regenerating the remaining wastewater streams and reusing them as e.g., rinsing water, the water cycle can be nearly closed. However, zero emission is still not possible because of the sludge production in the biological treatment, and because of the concentrate fraction, which is still to be further treated. Possibilities for concentrate treatment include vacuum evaporation and incineration [6], but need to be further investigated.

5. Conclusions

A step-by-step study of the water cycle in a company allows reducing significantly the water consumption. Making the water balance is useful to detect unknown water consumption, and is the basis for further optimization. Water Pinch or Water Scan methods allow deciding which streams can be reused, directly or after regeneration. Finally, the remaining wastewater can be included in an overall process scheme aiming at zero discharge of wastewater. For breweries, all three steps have been proven to be useful, although a zero discharge is not entirely obtained.

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