Reclamation of wastewater for industrial purposes – advanced treatment of secondary effluents for reuse as boiler and cooling make-up water

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Abstract
In this paper two industrial reuse applications are presented. The first one describes the reclamation of refinery/petrochemical effluents for reuse as boiler make-up water, an objective that is met by the employment of an advanced multi-barrier system, which includes ultrafiltration and reverse osmosis. The plant has been in operation for seven months and shows excellent performance, e.g. the level of silica, one of the most crucial parameters, is reduced from approximately 100 mg/l in the raw water to 6 µg/l in the boiler make-up water. The second case described involves the reuse of secondary municipal effluents as cooling make-up water. The multi-stage reclamation process includes nitrifying biological aerated filters (BAF) as a major process step. On average, ammonium is reduced from 49 in the inlet to 4 mg/l in the outlet of the BAF. This is essential as otherwise it could cause serious problems (biomass growth, corrosion) in the cooling water circuit. As cost calculations show, both reuse applications are viable. Furthermore, they are sustainable due to the savings of fresh water and the protection of the recipient waters.

Key words: BAF; industrial water reuse; reverse osmosis; ultra-filtration; water reclamation; water recycling;

1. Introduction

Water reclamation and reuse constitute one of the major trends in water management. The drivers are population growth, urbanisation, industrialisation in emerging markets, the pollution of raw water sources and to some extent, climate change. The consequences derived from these phenomena are water shortages and the excessive use of ground and surface water, which are putting severe pressure on the responsible authorities, municipal and industrial consumers. In the past 10 years, VA TECH WABAG has completed more than 20 water reclamation projects with a wide range of reuse applications (Lahnsteiner, 2005 & 2007). From these references, two industrial reuse examples in dry regions are presented in this paper, which involve the utilisation of municipal wastewater as cooling water (Baotou, China) and the employment of refinery wastewater as boiler feed water (Panipat, India).

2. Case studies

2.1. Industrial reuse in Panipat, Haryana, India

Panipat City (Haryana State) is located 90 km northwest of Delhi. Annual precipitation totals approx. 500 mm, but over 70 % of this rainfall occurs during the monsoon months of July to September.

The Indian Oil Corporation Ltd. Panipat decided to build a wastewater recycling plant (Tertiary Treatment Plant, TTP) as a response to the demand of the environmental authorities for zero discharge. This request was made due to the fact that no proper recipient is available in the Panipat area. Furthermore, the refinery has to recycle wastewater, as fresh water from the municipal network is restricted for use as potable water and in agricultural irrigation. In 2004, the contract was awarded to WABAG India and the plant, which treats both secondary refinery effluents and different refinery/petrochemical process effluents (Table 1), was commissioned at the end of 2006.

Table 1. : Panipat Refinery - Wastewater Streams

Panipat Wastewater Streams	
Secondary refinery effluent – WWTP I	400 m³/h
Secondary refinery effluent – WWTP II[1)]	300 m³/h
PX[2)]/PTA[3)] effluent including cooling tower blow-down	272 m³/h
Demineralisation regenerate of Panipat Refinery I	60 m³/h
Demineralisation regenerate of Panipat Refinery II[1)]	140 m³/h
Cooling tower blow-down of in-house Power Plant I	18 m³/h
Cooling tower blow-down of in-house Power Plant II[1)]	50 m³/h
Total wastewater	1,240 m³/h

[1)] Extension of refinery [2)] PX…..Para-Xylene [3)]PTA…..Purified Terephtalic Acid

The major parameters of the blended wastewater stream (inlet to TTP) consist of approx. 150 mg/l COD, < 10 mg/l BOD_5, 10 mg/l oil, 2,000 mg/l TDS and 100 mg/l silica.

Basically, the reclamation plant (design capacity = 900 m^3/h) incorporates clarification (including silica adsorption on magnesium hydroxide), pressure sand filtration, ultra filtration (UF) and reverse osmosis (3 stages) phases. The RO permeate is polished by mixed bed ion exchange filters and recycled. It is then used mainly as boiler make-up water in the refinery power plants (Fig.1).

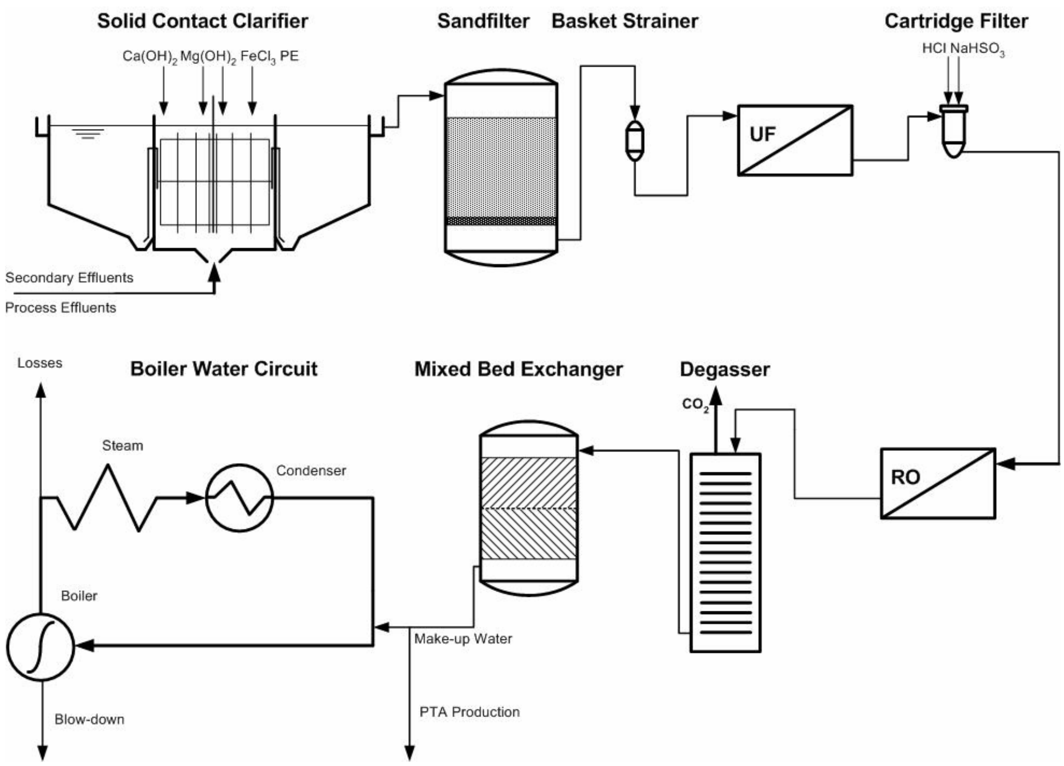

Fig.1 Panipat water reclamation and reuse process diagram

2.1.1. Ultrafiltration process step

Ultrafiltration is a pressure-driven, inside-out, hollow fibre system with 6 working skids (+ 1 stand by) and 18 horizontally mounted pressure vessels per skid. The system is operated in dead end mode. The major task of the UF is the reduction of the silt density index (SDI) and the removal of turbidity, as well as suspended and colloidal matter, in order to minimise fouling of the downstream reverse osmosis. However, the aforementioned impurities also cause fouling on the UF membranes and this is removed by regular backwashing with permeate. The backwash is enhanced by chemicals (chemical enhanced backwash - CEB with NaOCl and optional HCl) once a day. In addition, when a preset trans-membrane pressure (TMP) is exceeded, chemical cleaning with citric acid and sodium hydroxide in series is foreseen (cleaning in place, CIP). For this purpose, the membrane skid to be cleaned is taken offline and the chemical solutions are re-circulated over the membranes.

The UF was started up in November 2006 and its performance has been excellent with, e.g. SDI values of constantly less than 2 (inlet SDI is 7; the design value is 3).

During the past 5 to 6 months, the plant has been operated at the design flux of 46 l/m^2*h (max. capacity) with a cleaning demand, which was less than that defined in the process design. The plant was cleaned every 24 hours with chemical enhanced backwash (CEB) using NaOCl blended with NaOH (caustic NaOCl). Thus far, there has been no need for CEB with hydrochloric acid. Initially, cleaning in place (CIP) was completed several times during the start-up phase, but during the last six months of regular operation, was only carried out three times. Fig. 2 shows typical plots for permeability, trans-membrane pressure and the flux in skid D, and the effect of chemical enhanced backwash with caustic NaOCl.

On average, the COD level of 70 mg/l in the UF inlet is reduced to 33 mg/l in the UF outlet. The design flux of 46 l/m^2*h and a COD reduction of 37 mg/l, result in a COD removal rate of 1,702 mg COD/m^2*h, which can be regarded as a relatively high organic removal rate. However, as previously mentioned, this organic fouling can be removed relatively easily by CEB with caustic NaOCl. Whatever the case, permeability remains stable in the long-term.

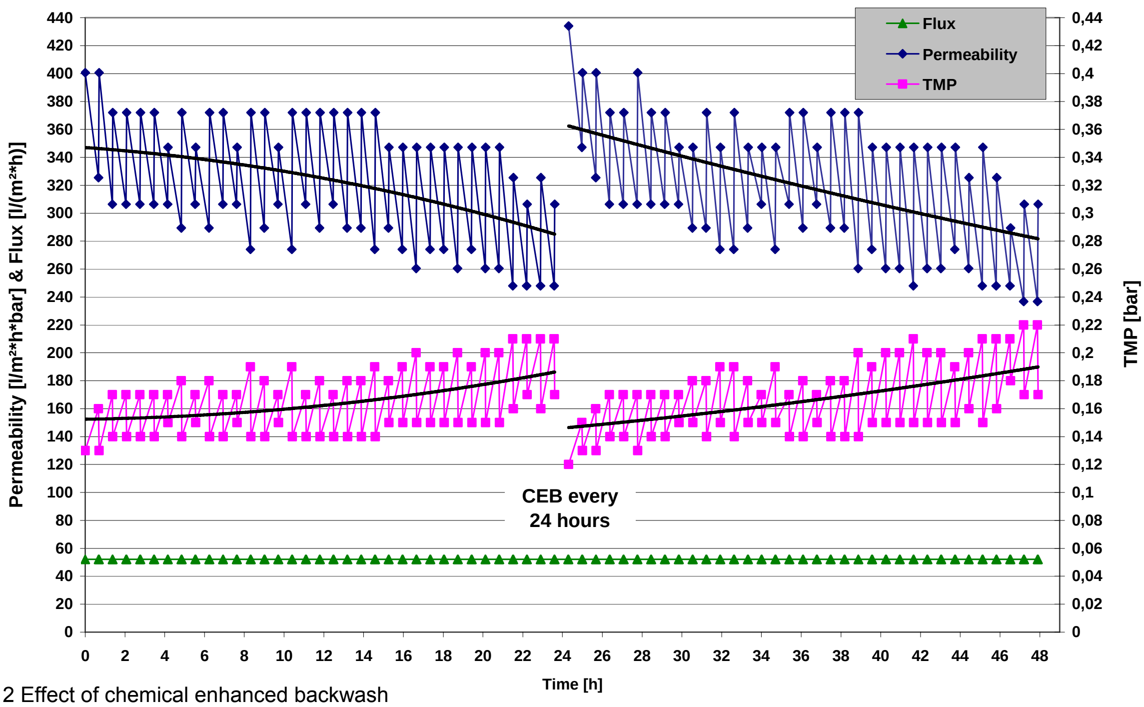

Fig. 2 Effect of chemical enhanced backwash

2.1.2. Reverse Osmosis

A three-stage reverse osmosis system is employed for desalination. As can be seen in Fig 3, the UF permeate is fed to R.O. stage I (low fouling composite membranes). The R.O. I permeate is further desalinated in R.O.II (low fouling composite membranes) and the R.O I reject is fed to R.O. III (sea water membranes). The R.O. III permeate is recycled to R.O. II. The recovery rate accomplished by this process configuration is 90 %. The R.O II permeate is degassed and, in order to allow further removal of dissolved solids, polished in mixed bed exchangers containing strong acid cat-ion and strong base an-ion resins mixed in a single vessel. The flow rates given in Fig. 3 are design values, the actual average flow rates were by approx. 7 % higher.

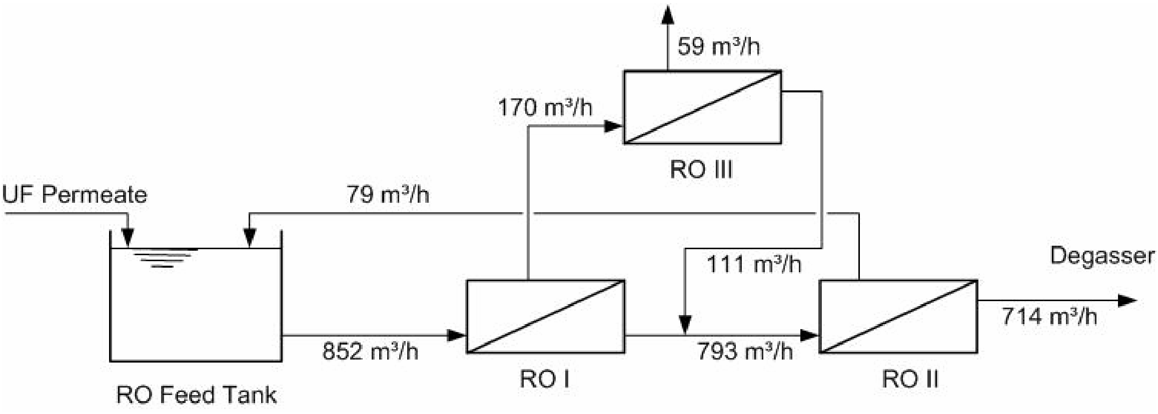

Fig. 3 Reverse osmosis process configuration

Fig. 4 shows the removal of conductivity and silica. Conductivity is mainly reduced in the reverse osmosis stage (from 4,000 to less than 5 µS/cm) and further cut in the mixed bed filter to less than 0.05 µS/cm. Silica is removed mainly by adsorption on magnesium hydroxide in the clarification stage and falls from approximately 100 mg/l to 10 mg/l. It is then cut further to less than 1 mg/l in R.O. I, 0.03 mg/l in R.O II and 0.006 mg/l (6 µg/l) in the mixed bed exchanger. This represents excellent removal efficiency, as 20 µg/l is the specified limit for boiler make-up water in various power plant guidelines (VGB, EPRI, etc.). Colloidal silica is zero as it is completely removed in the reverse osmosis stages.

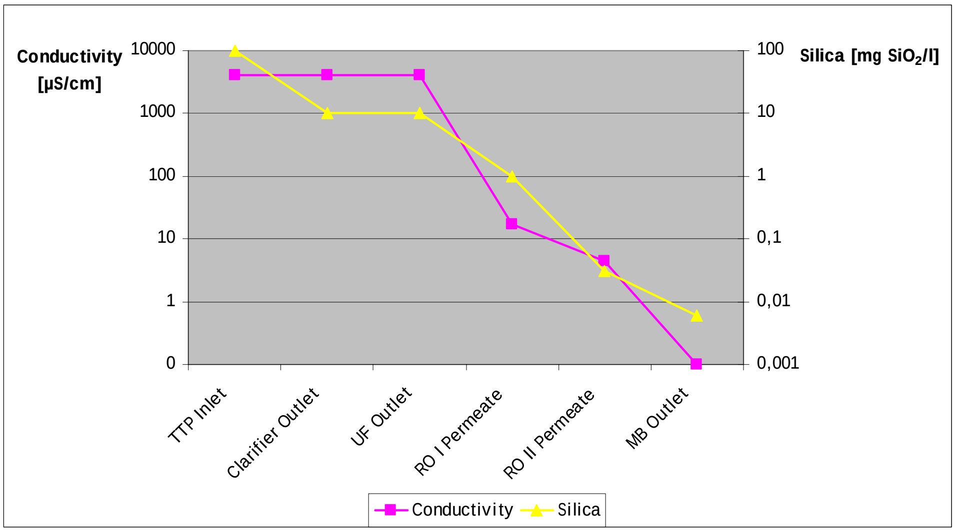

Fig. 4: Removal of Conductivity and Silica

Average feed quantity to the reclamation plant (high rate clarifier inlet) has amounted to 900 m^3/h and the production of demineralised has totalled 750 m^3/h with 83% overall recovery. As previously mentioned the authorities have stipulated that the refinery has to achieve zero discharge. However, temporarily the refinery has permission to dispose of the liquid wastes produced in the reclamation process (R.O. brine, etc.). Nonetheless, this official request will soon be met through the installation of evaporation and crystallisation.

The reclaimed water is used mainly as boiler make-up water and additionally as process water for the production of purified terephtalic acid (PTA), which is employed in the textile industry as a substitute for dimethyl terephthalate (DMT). The manufacture of PTA demands high quality water, e.g. zero colloidial silica and low TOC for the preservation of the catalyst, which is needed for the chemical reaction, and practically absolute softened water for the end product quality (textile elasticity).

The operating costs are approximately 25 Indian rupees (0.46 EUR/m^3) per cubic metre of reclaimed water. A rough breakdown of these costs is as follows: 6 rupees/m^3 (0.11 EUR/m^3) for energy, 6 rupees/m^3 (0.11 EUR/m^3) for chemical consumption, 4 rupees/m^3 (0.07 EUR/m^3) for labour and 9 rupees/m^3 (0.16 EUR/m^3) for others expenses such as maintenance and membrane replacement, cartridge filter elements, resins, etc. The total investment costs amounted to approx. EUR 10 million. The related capital costs, with 10 % interest and a 20-year depreciation period, amount to EUR 0.18 /m^3 (9.8 rupees/m^3). Therefore, total operating costs add up to EUR 0.64 /m^3 (35 rupees/m^3).

2.2. Industrial reuse in Baotou City, Inner Mongolia, China

Baotou is the largest industrial city in the autonomous province of Inner Mongolia. Annual precipitation in Baotou amounts to approx. 300 mm and therefore, due to high levels of industrialisation and a low level of natural water resource renewal, water reuse is a major priority in the city. In order to comply with national water conservation policy (NDRC 2005), as well as to save costs for freshwater from the municipal network, the Baotou Donghua Power Plant is re-using reclaimed municipal secondary effluent as make-up water for its cooling water circuit. The reclaimed nitrified water is purchased from Baotou City Yuan Tong Water Reuse Municipal Engineering Company Ltd., which operates a reclamation plant with a capacity of 40,000 m^3/d (Fig.5).

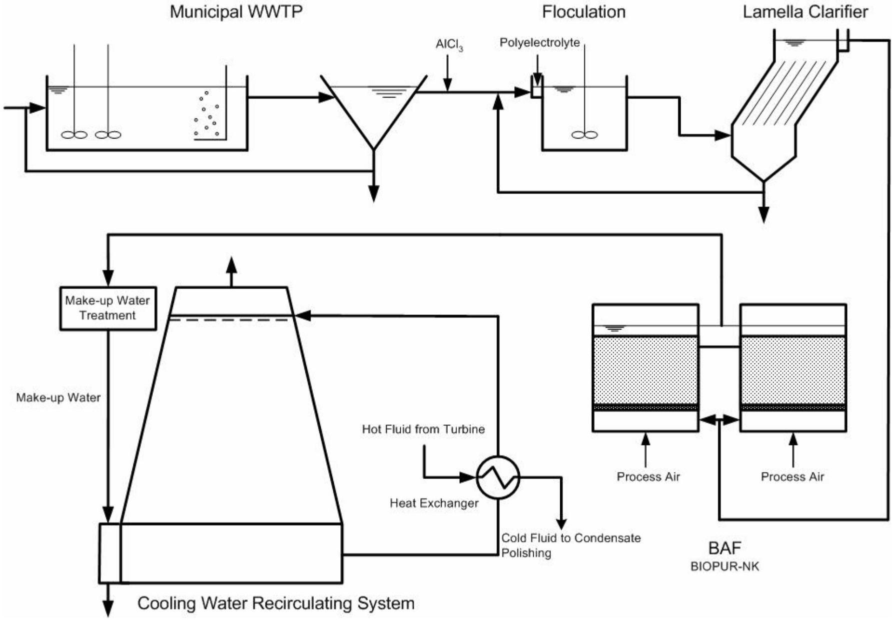

Fig.5 Baotou water reclamation and reuse process diagram

This tertiary treatment plant consists of coagulation, flocculation, lamella sedimentation and biological aerated filters (BAF, biofiltration) and is located on the site of the Baotou Donghedong WWTP.

The raw water consists of secondary effluent from the Baotou Donghedong and the Baotou Donghexi municipal wastewater treatment plants. The reclaimed water has to meet the quality requirements for the reuse of secondary effluents as make-up water for cooling water circuits laid down by the "Code for the design of wastewater reclamation and reuse BG/T50335-2002" (Table 2).

Table 2 Quality Standard for the Reuse of Secondary Effluent as Make-up Water for Cooling Water Circuits

No.	Parameter		
1		≤	6.0 ~ 9.0
2	SS [mg/l]	≤	-[1)]
3	Turbidity [NTU]	≤	5
4	BOD_5 [mg/l]	≤	10
5	COD_{cr} [mg/l]	≤	60
6	Fe^{++} [mg/l]	≤	0.3
7	Mn^{++}[mg/l]	≤	0.2
8	Cl^- [mg/l]	≤	250
9	Total hardness [$CaCO_3$mg/l]	≤	450
10	Total alkalinity [$CaCO_3$mg/l]	≤	350
11	NH_4-N [mg/l]	≤	10
12	TP [mg/l]	≤	1
13	TDS [mg/l]	≤	1,000
14	Cl-residual [mg/l]	≤	End 0.1 ~ 0.2
15	Faecal coliforms	≤	2,000

[1)] Definition of the Standard based on type of the cooling system

The secondary effluent is pre-treated by coagulation with aluminium chloride and static in-line mixers, flocculation, polymer dosing, and lamella sedimentation. The main process step is biofiltration (BAF, BIOPUR-NK), which employs granular carrier material (expanded clay), up-flow operation and excess head backwashing, in order to minimise filter media losses.

The advantages of biofiltration consist mainly of reduced space requirements and high process stability. The main reason for choosing compact BAF technology as a tertiary treatment step was the rather limited land available at the Donghedong WWTP.

The major purpose of the BAF process step is nitrification. As can be seen in Fig. 6, on average the ammonium level is reduced from 49 in the BAF inlet to 4 mg/l in the BAF outlet.

The removal of ammonium by nitrification is necessary, as it is a nutrient, which promotes microbiological growth in the power plant's heat exchanger and on the cooling tower filling (Loretitsch 2005). Additionally, ammonium can corrode the copper alloys used in heat exchangers. Another advantage of nitrification is that alkalinity is decreased significantly, which reduces the acid requirement for pH-control. Furthermore, a positive side effect of nitrification is provided by the nitrate produced, which along with phosphate, acts as a mild corrosion inhibitor.

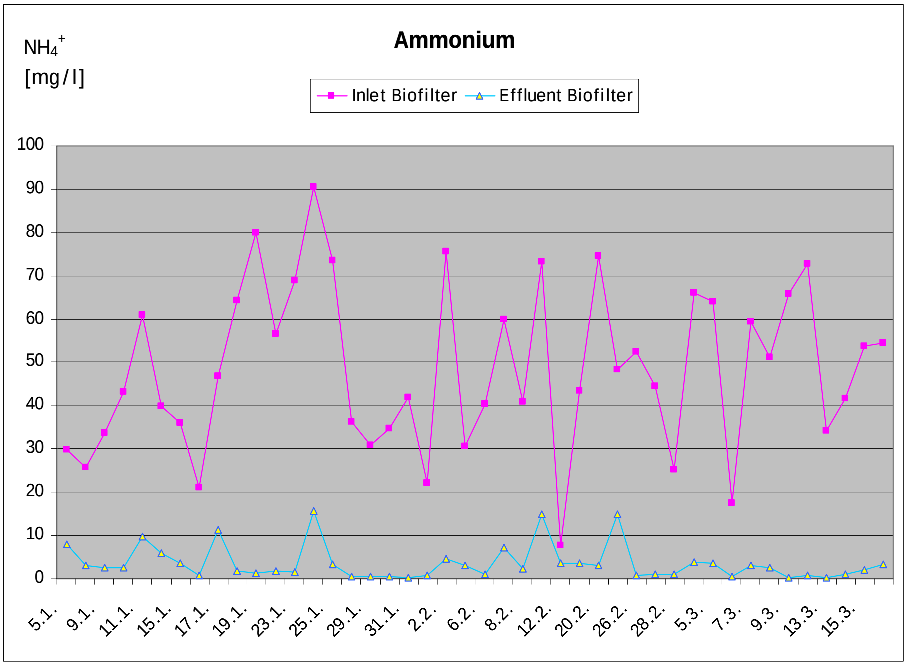

Fig.6 Baotou - ammonium removal in BAF

In addition to nitrification, some removal of suspended solids and carbonaceous compounds (COD, BOD_5) is accomplished in the BAF. As can be seen in Fig. 7, a moderate COD reduction is achieved (on average from 58 to 40 mg/l) as might be expected from biologically pre-treated wastewater (secondary effluent). This organic carbon reduction can be beneficial within the context of bio-fouling control (reduced biocide demand) in the cooling water circuit.

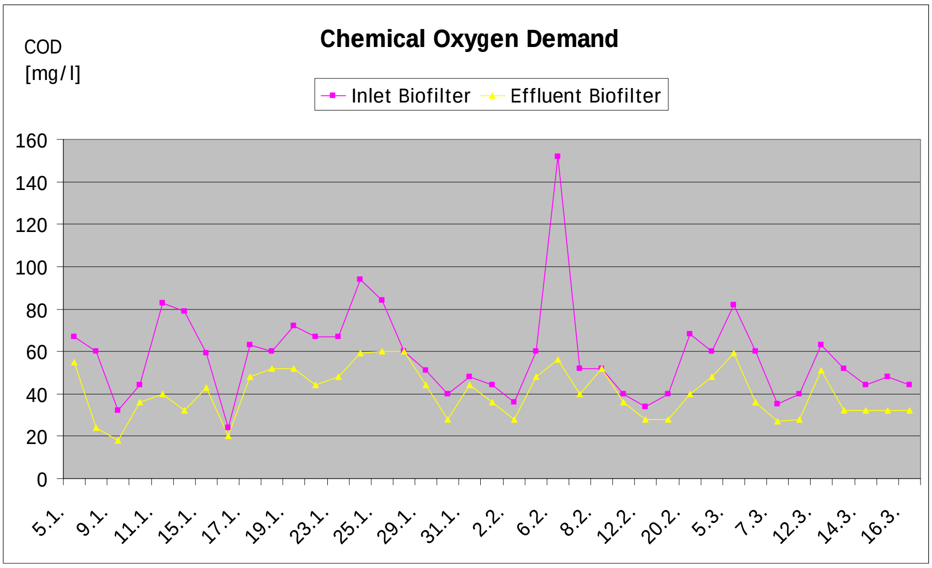

Fig.7 Baotou - COD removal in BAF

The make-up water treatment at the power plant consists of lime softening, flocculation/precipitation with ferric chloride and sand filtration. Sulphuric acid is added for pH-adjustment. Chlorine dioxide and an anti-scalant are dosed to the make-up water for circuit water conditioning. The power plant has been reusing reclaimed water for approximately 18 months and up to now no problems have occurred in the cooling process.

The operating costs are RMB 0.6/m^3 reclaimed water (EUR 0.06 /m^3). A breakdown of these costs shows that approx. RMB 0.2 /m^3 is required for energy, RMB 0.2 /m^3 for chemical consumption, RMB 0.1 /m^3 for labour and RMB 0.1 /m^3 for other expenses such as maintenance. The total investment costs including the raw water pipeline from Donghexi WWTP (approx. 7 km) and the reclaimed water pipeline to the power plant (approx. 7 km) amount to RMB 71 million (EUR 7.1 million). The capital costs calculated with a 10% interest rate and depreciation periods of 15 years for the electromechanical equipment and 20 years for the civil works are RMB 1.0 /m^3 (EUR 0.1 /m^3). Therefore, the total operating costs add up to RMB 1.6 /m^3 (EUR 0.16/ m^3). As the costs for fresh water from the municipal network are RMB 3.3 /m^3, the power plant achieves considerable savings.

In general, it can be stated that the reuse of secondary effluent as cooling make-up water is an ideal application, as large quantities of relatively low quality water are required for cooling purposes. Furthermore, this practice is sustainable as substantial amounts of fresh water can be saved. This is of great importance due to the fact that ground water levels in Inner Mongolia have declined markedly and that the flow of Yellow River, which is located some 10 km south of the power plant, has decreased rapidly in recent decades, causing the river to dry up every year in the downstream regions of eastern China.

3. Conclusions

The aforementioned industrial water reclamation and reuse case studies clearly indicate that this practice is feasible and, in both cases essential, in order to save fresh water and boost security of supply. Moreover, at Panipat, strict environmental requirements have forced the refinery to recycle the wastewater. In this context, advanced technologies such as membrane filtration are gaining in importance, especially in cases where the functioning of industrial processes has to be guaranteed. Whatever the case, water reuse constitutes a major factor in sustainable development, especially in arid and semi-arid regions.

4. Acknowledgements

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