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Integrated Design Methodology for Wastewater Treatment Plant

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An integrated design methodology has been formulated to systematically design a wastewater treatment plant for industrial effluents. Wastewater characteristics, plant information, reuse water and discharge effluents criteria are the basic information required for process design. The generic flowsheet for the wastewater treatment plant is presented and heuristics are developed to guide the designer to come up with a preliminary process design. A simulation code has been developed which incorporates design equations for the process units and accepts experimental data to regress model parameters for process simulation. Finally, flowsheet alternatives are compared to obtain the optimum process flowsheet. Sensitivity analysis can be performed to evaluate the impact of variations on plant performance. The workflow among various stakeholders to reach the final design is also discussed. The methodology is illustrated for the case of dyeing effluent treatment.

1. Introduction

Industry consumes huge amount of fresh water, depleting a valuable resource required for everyday human activities. In addition, wastewater effluents loaded with pollutants often pose significant hazards to the environment. It is therefore important to have high-performance and low-cost wastewater treatment plants (Rodriguez-Roda et al., 2000; Putra and Amminudin, 2008) to treat and reuse industrial effluents. Despite its importance, many wastewater treatment plants are still designed based on experience, leading to high consumption of chemicals, plant failure in the presence of disturbances and inappropriate selection of wastewater treatment techniques such as coagulation, adsorption, biotreatment, Fenton reaction, ozonation, multi-media filtration, membrane filtration, etc. An integrated design methodology is therefore important to design a high-performance and low-cost wastewater treatment plant. The general design methodology using dyeing industry as an example is illustrated below.

2. Case Study – Dyeing Industry

The dyeing process consumes humongous amount of water, ranging from several thousand to over ten thousand cubic meters per day for a typical dyeing plant. The

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heavy water requirement for dyeing industry stems from a number of water-intensive steps in the dyeing process. A woven cotton dyeing process usually involves six pretreatment steps: grey inspection, singeing, desizing, scouring, bleaching and mercerization, while singeing, desizing and mercerization are usually not required for knitted cotton dyeing.

Table 1: Major chemicals used in various dyeing processes

Process	**Major chemicals used for the process**
Grey inspection	No chemicals added
Singeing	No chemicals added
Desizing	➢ Removing starch-based sizes: enzymes (e.g. amylases) or mineral acids (e.g. dilute sulphuric acid) ➢ Removing water-soluble synthetic sizes: Na_2CO_3, non-ionic surfactant, sequestering agent
Scouring	➢ NaOH or Na_2CO_3 ➢ Anionic or non-ionic surfactant (e.g. alcohol ethoxylates)
Mercerization	➢ NaOH ➢ Wetting agent (e.g. cresylic acid)
Bleaching	➢ Hydrogen peroxide bleaching: H_2O_2, bleach activators such as NaOH, surfactant, H_2O_2 stabilizer such as sequestering agents ➢ Sodium hypochlorite bleaching: NaOCl, NaOH, Na_2CO_3, wetting agent; followed by chlorine removal: mineral acid (e.g. acetic acid)
Polyester dyeing (^{1}Carrier dyeing only; ^{2}High temperature dyeing only)	➢ Disperse dyes ➢ Dispersing agent (e.g. polymeric versions of sodium dinaphthylmethane sulphonate) ➢ Carrier^1 (e.g. aromatic hydrocarbons, phenols, aromatic acids) ➢ Levelling agent^2 (e.g. non-ionic aliphatic polyglycol ether) ➢ Sequestering agent (e.g. EDTA) ➢ Acid / buffer (e.g. acetic acid)
Cotton dyeing	➢ Reactive dyes ➢ Alkali (e.g. Na_2CO_3, NaOH) ➢ Salt (e.g. NaCl, Na_2SO_4) ➢ Mild oxidizing agent (e.g. sodium 3-nitrobenzenesulfonate) ➢ Wetting agent, non-ionic or anionic surfactant (e.g. salt of phosphoric acid ester)
Finishing	➢ Dispersions of polymers (polyacrylesters, polyethylene, silicones)

The fabric is then dyed with reactive dyes, followed by washing to remove any unfixed dyes on its surface. Finally, finishing is applied to increase the aesthetic value, durability and comfort of the textile goods. For polyester, only grey inspection and heat-setting are required before dyeing with disperse dyes. Common chemicals used in these processes are summarized in Table 1. Wetting agents and surfactants are applied in various processes to provide better penetration of chemicals into fabric to allow more even treatment. Common wetting agents include alkylarylsulphonates, sulphated alcohols, and cresylic acid, mixture of o-, m- and p-cresols, mixed with solvent additives such as cyclohexanol. Sequestering agents such as ethylenediaminetetraacetic acid (EDTA) are also added if the presence of metal ions produces precipitates that affect the process.

Some of the chemicals listed in Table 1 are known to impose significant hazard to the environment. For example, some reactive dyes are either toxic or can be biologically converted to toxic or carcinogenic compounds (Brown and De Vito, 1993). Azo dyes, the most common type among commercial dyes, form highly carcinogenic aromatic amines as degraded products (Pinheiro et al., 2004). These chemicals have to be removed from the wastewater so that it can be either safely discharged or reused for dyeing processes. For this purpose, it is desirable to build a low-cost, high-performance wastewater treatment plant to treat and reuse the wastewater, which will be discussed below using the integrated design methodology.

3. Integrated Design Methodology

An integrated design methodology has been formulated for the systematic development of a wastewater treatment plant. Dyeing effluents are first characterized to provide basic information for process design. Reuse water and discharge effluents criteria are also needed to ensure the treated water is suitable for reuse or discharge. Process flowsheet of the wastewater treatment plant is then generated with the guidance of heuristics. Design equations and parameters are identified for all process units and are incorporated into a simulation code for process evaluation. Experimental data can be entered into the simulation code to regress model parameters for process simulation. Flowsheet comparison and sensitivity analysis can be carried out to obtain the optimum process flowsheet.

3.1 Input Information for Plant Design

Wastewater characteristics such as chemical oxygen demand (COD), 5-day biochemical oxygen demand (BOD_5) and solids content are important parameters to design the wastewater treatment plant. Typical wastewater characteristics from various processes in a dyeing plant is summarized in Table 2.

Plant information such as chemicals used in the dyeing plant and its production cycle also provide information for process design. Reuse water criteria (e.g. U.S. EPA, 2004) and discharge criteria (e.g. Department of Environmental Protection of Guangdong Province, 2005) have to be obtained to evaluate the performance of the wastewater treatment plant.

3.2 Construction of Flowsheet for Wastewater Treatment

The wastewater treatment plant is then designed based on wastewater characteristics and its generic flowsheet is depicted in Figure 1. Biotreatment is commonly used in the wastewater treatment of dyeing effluents. Pretreatment and water purification may be needed depending on the wastewater characteristics. The expanded flowsheet for these two subprocesses are depicted in Figure 2. Heuristics are provided to guide the decision process and the selection of treatment techniques. For example, pretreatment is needed if the wastewater has low biodegradability ($BOD_5/COD < 0.4$) or contains chemicals present at a concentration inhibitory or toxic to biotreatment. Fenton reaction is commonly used in pretreatment to increase the biodegradability of the effluents, while ion exchange or adsorption is used to remove chemicals such as heavy metals that are detrimental to biotreatment.

Table 2: Chemicals contained in effluents of various dyeing processes and their general characteristics (Correia et al., 1994)

Process	**General characteristics of wastewater**			
	COD	BOD (mg/L)	TS (mg/L)	pH
Desizing	High	1,700-5,200	16,000-32,000	
Scouring		50-2,900	7,600-17,400	10-13
Mercerization		45-65	600-1900	5.5-9.5
Bleaching		90-1,700	2300-14400	8.5-9.6
Polyester dyeing and washing	High	480-27,000		
Cotton dyeing and washing	High	11-1,800	500-14,100	5-10
Finishing	Vary			

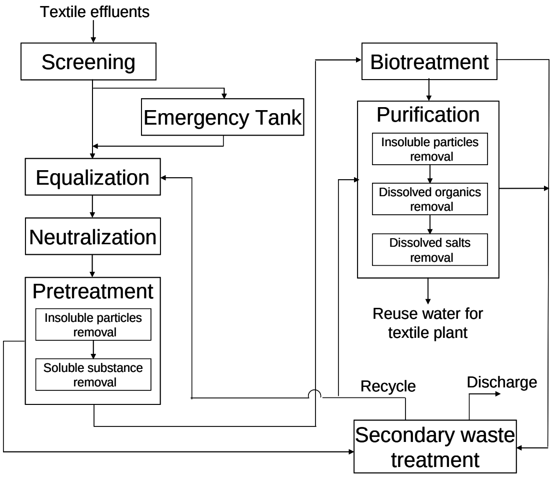
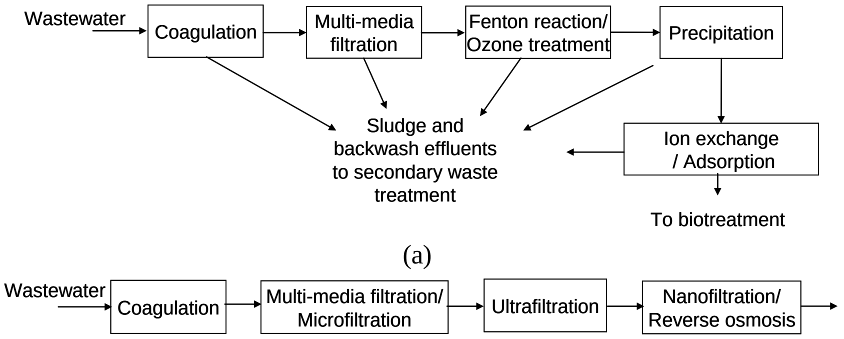


Figure 1: Generic flowsheet of wastewater treatment plant

3.3 Process Simulation of Wastewater Treatment Plant

A simulation code is developed to simulate the performance of a wastewater treatment plant. It incorporates design models and accepts experimental data to regress model parameters of the process units for process evaluation. Figure 3 uses multi-media filtration as an example to illustrate the workflow. Column experiments are carried out for multi-media filtration, which collect samples along the column at different times during the experiment. Total suspended solids (TSS) content is then measured for all samples collected. Experimental data are entered into the simulation code for the regression of model parameters for multi-media filtration column (Yao et al., 1971). The performance of industrial scale multi-media filter columns are then estimated.



(a)

(b)

Figure 2: Expanded flowsheet for subprocess (a) pretreatment and (b) purification

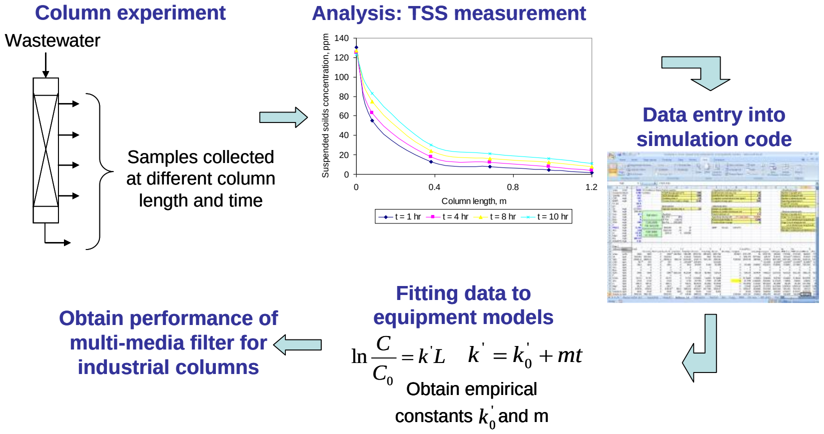


Figure 3: Simulation code acquires experimental data for model parameters estimation

3.4 Flowsheet Evaluation

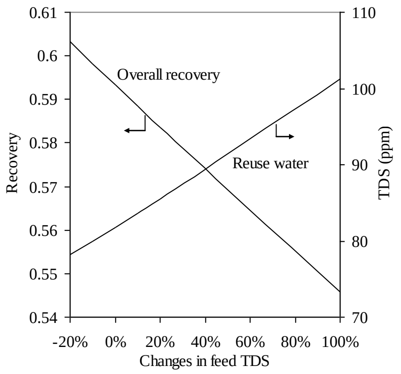


Figure 4: Effect of changes in feed TDS on recovery and TDS for reuse water

Various flowsheet alternatives are then compared in the simulation code to obtain the process flowsheet that provides the best performance. Simulation results are compared with the reuse water and discharge effluent criteria to ensure the water to be reused in the dyeing plant or discharged to the environment meet with the specifications. Sensitivity analysis is also carried out to evaluate the impact of variation of the design parameters on plant performance. The capability of the plant facing disturbances such as variation in influent flowrate and water quality is also studied to ensure sufficient plant capacity is designed for such situations. For example, the change in feed TDS on overall recovery and water quality of reuse water is depicted in Figure 4.

4. Conclusions

The integrated design methodology for designing a wastewater treatment plant for dyeing effluents is presented such that water can be reused in dyeing processes, minimizing the demand of valuable fresh water. Water characterization, heuristics-guided process design, experiments, process simulation and process alternatives comparison comprise the key of the design methodology. This methodology emphasizes the importance of the integration of three elements: process synthesis, experiments and simulation, allowing the design of a high-performance and low-cost wastewater treatment plant. This methodology can be extended to other industrial effluents such as electroplating industry and pulp and paper making industry. Efforts in this direction are now underway.

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