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Application of water pinch technology in minimization of water consumption at a refinery

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ABSTRACT

Water is the most significant entity that controls local and global development. The present research involves property integration technique, graphical and mathematical; to first establish accurate targets for maximum direct recycle of process sources, as well as minimum waste discharge and fresh water consumption at an oil refinery. Property-based water allocation network is designed for the process based on previously identified targets. Chemical oxygen demand (COD) and hardness properties are taken as pollutants (contaminants) and treated as single and double contaminant approach to dig out fresh water demand in the process. Both graphical and mathematical programming techniques exhibit the same water reduction of 149.0 m^3/h (43.8%) and 208.0 m^3/h (61.18%) for COD and hardness case, respectively, in single contaminant approach. While, a new double contaminant mathematical programming has shown a significant reduction of 39%, based on mixing rules of properties. Among the multiple water networks, one possible water allocation network is developed based on mass exchange.

1. Introduction

Water demands are growing every year as a result of the booming world population. A population report on the environment and water issues has estimated that more than 2.8 billion people in 48 countries will lack access to adequate water supplies by 2025 (Wang and Smith, 1994). Reduction of water consumption has received attention of many researchers all around the world (El-Halwagi and Manousiouthakis, 1989).

Water is extensively utilized in chemical, petrochemical, food and drink, pulp and paper, textile and in many other industries. Stricter environmental regulations, scarcity of quality industrial water and the rising cost of wastewater treatment have encouraged process plants to reduce water usage. Concurrently, the development of systematic approaches for fresh water reduction, reuse and regeneration within a process plant has shown extensive progress in recent years (Tan et al., 2007). Pinch technique was proposed many years before by Linnhoff et al. (1982). The application of pinch technique, in the area of water related process, was first introduced by Wang and Smith (1994). In later times, a graphical method was proposed to determine the fresh water target. This proposed method got the attention of many researchers (Wang and Smith, 1994). Later on, many industrial practices proved the success of this technology. Sorin and Bédard presented the evolutionary table method to estimate the fresh water target (Sorin and Bédard, 1999). A graphical method called as "The Water Surplus Diagram" was also proposed to estimate the targets of fresh water (Hallale, 2002). Even though, this method had created the right pinch points but it was tedious. Manan et al., after some time, proposed a non-iterative numerical method, water cascade analysis, for fresh water targets calculation (Manan et al., 2004). He addressed that their method could provide important insights on pinch-causing streams and water allocation but could not be achieved by using the graphical technique of water surplus diagram by Hallale (2002). El-Halwagi et al. proposed another graphical method to determine the targets for fresh and wastewater, by locating various pinch points (El-Halwagi et al., 2003; El-Halwagi, 2006). Prakash and Shenoy had also suggested a graphical method to calculate the fresh water targets based on the cumulative flow-rate/contaminant-load curves (Prakash and Shenoy, 2005). Most of the researchers have observed the process streams in detail, either graphically or mathematically, to determine pinch point and fresh water targets. In fact, if the insights of the pinch technique are incorporated, the pinch point can be determined before target calculation resulting in reduced objective calculation struggle.

In the case of recycle/reuse arrangements, Gabriel and El-Halwagi have described a simplified formation that eliminated the mixing of different streams to avoid bilinear terms and to yield

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a convex problem formulation (Gabriel and El-Halwagi, 2005). This approach has avoided the bilinear terms of the mass balances and simplified the problem without paying any attention to the configurations of potential interest. The model was stretched to be based on different properties, instead of dealing only with compositions (Ponce-Ortega et al., 2010). Many scientists have addressed the problem of global optimization of recycle and reuse networks, based on properties, using NLP and MINLP formulations (Ponce-Ortega et al., 2009; Nápoles-Rivera et al., 2010; Yang and Grossmann, 2013; Karuppiah and Grossmann, 2006; Ahmetovic and Grossmann, 2011). Bagajewicz et al. had also performed a review of various graphical and mathematical programming techniques to design and retrofit water networks (Bagajewicz et al., 1999). Their research has also concluded that the optimal water allocation and treatment is moving toward the use of mathematical programming techniques, due to the severe limitations in handling multi-component systems by graphical method (Bagajewicz, 2000).

In this study, water pinch technique is adopted to determine the minimum fresh water requirements, maximum recycle/reuse and minimum wastewater discharge in a process. Property integration of COD and hardness is selected as water contaminants (pollutants). Both properties (contaminants) are analyzed by considering single (one property at a time in process) and double (two properties together in the same time) contaminant approach. In the pinch technique, a graphical method is used to carry out the required objective and then the mathematical programming is developed to verify the graphical method results. Mathematical model has also proposed the allocation of one possible water allocation network of source stream(s) to the demand stream(s). The results coming out of this study have shown a great degree of accuracy in comparison to other method proposed by NabiBidhendi et al. (2010).

2. Methodology and case study

The selected process/unit is firstly divided into sinks and sources streams. Sinks streams are categorized as inlet streams of the selected unit/process and the outlet streams are considered as sources. Fresh water and wastewater are also placed under source category, though, some of the waste streams cannot be used/reused as a source or inlet stream.

Target for fresh water is determined by considering all the sinks and sources in the process. The sinks and sources are arranged in ascending order of their maximum property loads as property loads are analogous to mass loads (Kazantzi and El-Halwagi, 2005). El-Halwagi and Prakash have shown that the ascending arrangement of sources and sinks provide a simplified target and design arrangement (El-Halwagi et al., 2003; Prakash and Shenoy, 2005; Gabriel and El-Halwagi, 2005). For maximum property load of a sink, consider a process with a number of process sinks (N_{sinks}). G_j is the flow rate with an inlet property, p_j^{in} for each sink j, which satisfies (1),

$$p_j^{\min} \le p_j^{in} \le p_j^{\max} \quad \text{where} \quad j = 1, 2, \ldots, N_{sinks} \tag{1}$$

where $p_j^{\min}$ and $p_j^{\max}$ are the lower and upper bounds on permissible property to unit j. Let us consider that the plant has a number $N_{sources}$ of process sources for potential reuse and replacement of the fresh material. W_i is the flow rate with a given property p_i, for each source i, where; p_{fresh} is the property value for fresh available resource. In the event of numerous sources mixing, it becomes essential to evaluate the property of the mixture as a function of the flow rate and property of each stream. The mixing rule for estimating the resulting property of the mixture can be written as:

$$F \times \psi(p) = \Sigma_i F_i \times \psi(p_i) \tag{2}$$

where $\psi(p_i)$ is the property-mixing operator, p is the property of the mixture and F is the total flow rate of the mixture which is given by:

$$F = \Sigma_i F_i \tag{3}$$

The property-mixing operators can be evaluated from first principles or estimated through empirical or semi-empirical methods. Recalling the definition of density, we have:

$$\frac{F}{\rho} = \left(\frac{F_1}{\rho_1}\right) + \left(\frac{F_2}{\rho_2}\right) \tag{4}$$

By comparing (2) and (4), the density-mixing operator can be defined as:

$$\psi(p_i) = \frac{1}{p_i} \tag{5}$$

I.e. property load of a stream can be expressed as,

$$M_i^{Source} = W_i \times \psi(p_i) \tag{6}$$

For source i, let,

$$y_i = \psi(p_i) \tag{7}$$

Therefore, (6) can be written as follows:

$$M_i^{Source} = W_i \times y_i \tag{8}$$

Similarly, (1) can be interpreted for the sink constraints in the property-mixing operator as:

$$\psi_j^{\min} \le \psi_j^{in} \le \psi_j^{max} \tag{9}$$

By keeping in mind that the fresh source has always superior properties compared to all other streams, and the sink constraint is given by:

$$\psi_j^{fresh} \le \psi_j^{in} \le \psi_j^{max} \tag{10}$$

where

$$\psi^{fresh} = \psi(p_{fresh}) \tag{11}$$

Therefore the maximum property load of a sink can be calculated as:

$$M_j^{Sink,max} = G_j \times \psi_j^{\max} \tag{12}$$

For sink j, consider,

$$z_j^{max} = \psi_j^{\max} \tag{13}$$

By incorporating (13) into (12), we reach to the following expression:

$$M_j^{Sink,max} = G_j \times z_j^{\max} \tag{14}$$

It is quite interesting to see the similarity between (8) and (14), which depicts that the property loads are analogous to the mass loads.

After calculating the loads of each sink and source stream, sink and source composite curves are created, respectively, using superposition. Fresh water demand is calculated by sliding source composite curve on the fresh line depicting on the x-axis while keeping it below sink composite curve on the same graph. Source composite curve is pushed until it touches the sink composite curve to a certain point. This point of interaction is entitled as *Property-Based Recycle Pinch Point* and can be seen in Fig. 1.

Kazantzi and El-Halwagi have provided some design rules for constructing the pinch diagram for minimum demand of fresh water, maximum use of recycled wastewater and minimum wastewater disposal (Kazantzi and El-Halwagi, 2005) and these are: