WATER NETWORK OPTIMIZATION FOR ENERGY SAVINGS AND DISCHARGE REDUCTION: A DIFFERENT PERSPECTIVE ON A CRITICAL PROBLEM FOR THE CHEMICAL INDUSTRY

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Abstract

The chemical, polymer and petrochemical process industry plays a critical role in creating, manufacturing and developing products for the service of mankind. This vital industry has been under significant pressure in recent years. The cost of raw materials has steadily increased while selling prices and profit margins have gradually eroded due to increased competition from a global economy. This has resulted in the industry implementing several cost reduction measures including a push to develop strategies to simultaneously minimize energy usage and environmental discharge via recycling and re-using process streams in general and water streams specifically. Water is a relatively inexpensive solvent that is widely used and presents minimal toxicity and safety concerns. Most processes have freshwater added to different unit operations (i.e., sinks of water) and generate several wastewater effluent streams (i.e., sources of water) at different pollutant compositions and temperatures. When considering recycling these water streams, there is a need to identify those networks that will present the highest potential return or “bang for the buck” (both from the perspective of energy savings as well as wastewater discharge reduction). Traditional approaches in this area focus on the use of pollutant composition as the key variable. This work presents the problem of allocating effluent streams with temperature as the limiting factor instead of composition of the pollutant. Development and application of a new design methodology resulting in the generation of water recycle networks is presented with insights from an industrial perspective

Keywords

Water, Wastewater, Optimization, Networks, Effluent, Environmental, Economics, Sustainability, Cost.

Introduction

The chemical process industry is facing increased pressure to come up with processes and products that are cheaper and more environmentally friendly. Besides, the globalization of the world economy has led to increased competition. The key to tackling all these challenges lies in process integration, which involves leveraging all process resources in an optimal fashion so as to reduce overall cost and increase productivity while simultaneously lowering adverse environmental impact. However, previous attempts at process integration were arbitrary or based on experience. There is a need for accurate and systematic ways to reduce costs and improve overall process performance in the chemical process industries. Every chemical process is an integration of two dimensions namely, the mass dimension and the energy dimension. As part of process integration, the process needs to be optimized from both dimensions via energy and mass integration respectively. The oil crisis in the seventies led to a search for efficient means to reduce energy usage in plants, which finally led to the development of heat exchange networks. Furman and Sahinidis, 2002, present a comprehensive summary of various developments in this field. Among the various species in a chemical process, water is critical and is widely used across several industries. It is a relatively inexpensive and useful solvent which is easy to handle and presents minimal toxicity and safety concerns. In a typical chemical process, water may play several roles. It may act as a solvent; enable heat removal, washing and other post production activities besides being used in environmental compliance devices. Wastewater reduction and water conservation are becoming increasingly more important issues in process industries. More stringent environmental regulations, concerns over long-term health effects on humans and nature, and the future availability of “clean” water resources are just a few of the factors that are driving efforts toward improvements in water conservation and wastewater reduction in manufacturing processes.

These critical concerns have refocused efforts over the past decade toward identifying cost-effective wastewater reduction and water conservation process designs, involving direct recycle and reuse of water that can be implemented within a variety of process industries (Wang and Smith, 1994; Dhole *et al.* 1996; Polley and Polley, 2000; Hallale, 2002; El-Halwagi, 1997; Parthasarathy and Krishnagopalan, 2001; Dunn and Wenzel, 2001; Parthasarathy *et al*., 2001a, b). However, one area that has not been adequately addressed is the problem of allocating effluent streams with temperature as the limiting factor instead of (or along with) composition of the pollutant. There have been a few recent papers (Bagajewicz *et al.*, 2002; Savulescu *et al.*, 2002) that have considered related aspects of this problem. In practice, temperature of a stream can play an equal (if not more important) role as its composition. In most industrial processes, the capital required to install a "separation technology" to remove pollutants from a dilute wastewater stream (so as to reduce its composition, thus enabling it to be recycled) is generally higher than the capital required for installation of a heat exchanger to recover energy. Also, the unit cost of steam is significantly higher than the unit cost of water which results in projects involving steam savings possessing higher returns on investment than those projects focused only on water. It must be noted that the scenario is different in other areas of the world (such as Europe). Solutia has a European plant which has several water recycle and recovery projects in place as the unit cost of water is much higher in Europe, thus enabling justification of these projects. Therefore, including temperature constraints in the allocation optimization is a critical problem that is defined and explored further in this paper. It is assumed that compositions of various effluent streams are low enough so as to not build up due to recycle.

Problem Definition

The following problem is addressed. Given a process with various aqueous effluent streams (at different temperatures) and several unit operations which require fresh water at different inlet temperatures (and can accept these effluent streams when they are recycled), it is desired to identify the water network that will maximize energy and water savings at minimum overall cost. This problem can be represented mathematically within the mass integration framework (Refer Figure 1) which is particularly useful for integration, allocation, generation and separation of species and streams (El-Halwagi *et al.*, 1996). First, sources and sinks are defined in the given process. Sources are process streams that carry the targeted species. Sinks are process units capable of processing the sources carrying the targeted species. Sinks include reactors, separators, washers, heaters, coolers, pollution-control facilities etc. The problem is represented mathematically in equations 1-11. Certain sources may be "intercepted" to change its temperature (represented by $T_{i,m}^{Source,Int}$ in equation 7) so as to make it more amenable for recycle. This interception is a heat exchange operation carried out by incorporating a heater or cooler (Equations 7 and 8). The overall problem objective is to minimize the total annualized cost of the water network.

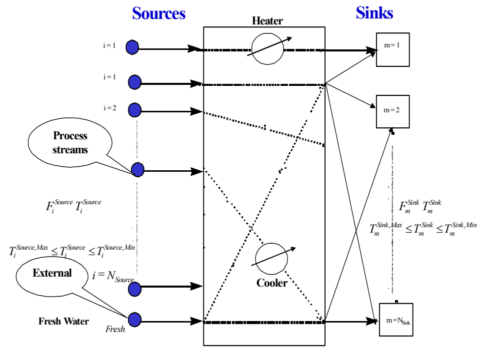

Figure 1: Problem representation

Source and Sink Balances

$$F_i^{Source} = \sum_{m=1}^{N_{Sink}} f_{i,m} \tag{1}$$

$$F_m^{Sink} = fresh_m + \sum_{i=1}^{N_{Source}} f_{i,m} \tag{2}$$

$$Fresh = \sum_{m=1}^{N_{Sink}} fresh_m \tag{3}$$

$$F_m^{Sink} T_m^{Sink} = fresh_m T^{Fresh} + \sum_{i=1}^{N_{Source}} f_{i,m} T_i^{Source} \tag{4}$$

Source and Sink Temperature Bounds

$$T_i^{Source,Max} \le T_i^{Source} \le T_i^{Source,Min} \tag{5}$$

$$T_m^{Sink,Max} \le T_m^{Sink} \le T_m^{Sink,Min} \tag{6}$$

Source/Sink Interception Constraints

$$F_m^{Sink} T_m^{Sink} = fresh_m T_m^{Fresh,Int} + \sum_{i=1}^{N_{Source}} f_{i,m} T_{i,m}^{Source,Int} \tag{7}$$

Heater/Cooler Heat Balances

$$Q_{i,m} = f_{i,m} C_p \left(T_{i,m}^{Source,Int} - T_{i,m}^{Source} \right) \tag{8}$$

Overall Problem Objective

$$\min\ (\mathrm{TAC}) \quad \text{for } \mathrm{i} = 1,2,\ldots\ldots\ldots, \mathrm{N}_{\mathrm{Source}} \quad \text{for } \mathrm{m} = 1,2,\ldots\ldots\ldots, \mathrm{N}_{\mathrm{Sink}} \tag{9}$$

where,

$$TAC = \Gamma\left(Cost^{Heat}, Cost^{Cool}, Cost^{Other}\right) \qquad (10)$$

The cost of heating (or cooling) is a function of $Q_{i,m}$ as represented by $Cost^{Heat} = \delta(Q_{\mathrm{i,m}})$ and $Cost^{Other}$ refers to other costs such as the cost of piping, pumping, filters etc. An example is the cost of piping which can be represented as follows

$$Cost^{Piping} = \mathrm{cost}_{unit}^{Piping} \sum \mathrm{I}_{i,m} Dist_{i,m} \qquad (11)$$

where $\mathrm{cost}_{unit}^{Piping}$ is the unit cost of piping and $\mathrm{I}_{\mathrm{i,m}}$ and $Dist_{\mathrm{i,m}}$ are the integer variables (denoting a match between source *i* and sink *m*) and actual distance (from source *i* to sink *m*) respectively

Case Study

The case study is one of several batch polymerization reactions at Solutia's Springfield, MA, site. Solutia Inc. was formed in 1997 from the chemical businesses of Monsanto Company. Poly vinyl butyral is one of the key products of the business. Figure 2 is a generic block description of this process. Each block has more than one unit operation (for instance, the reactor block has multiple reactors). Details of the process flow sheet have been presented in this fashion for maintaining the confidentiality of proprietary information. The raw materials are added to the reactor from the silos. After reaction, the product is washed, dried and finished. The used solvents are recovered in a recovery operation.

Results

This analysis was conducted at Solutia's Springfield, MA, site in the early part of 2003. The overall objective was to identify projects that allowed for water and energy savings at reasonable investment cost. The solution strategy can be described as follows: The initial fresh water demand for the whole process was estimated. Several optimization runs were conducted. For each run, the total fresh water demand was reduced from the initial demand by a certain percentage. In addition, specific cases were considered at each reduced fresh water flow. One instance would include dealing with a water stream from an adjacent process. Cases were considered with this stream included as well as excluded from the analysis. As the stream belonged to a different process, it may become difficult to justify its use due to possible cross contamination concerns and availability constraints.

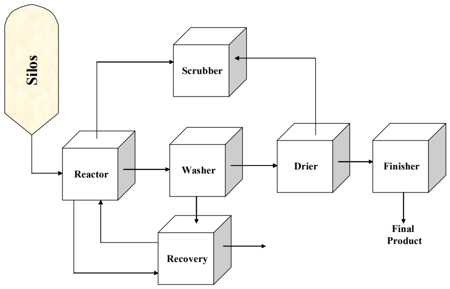

Figure 2: Poly vinyl butyral process flow sheet

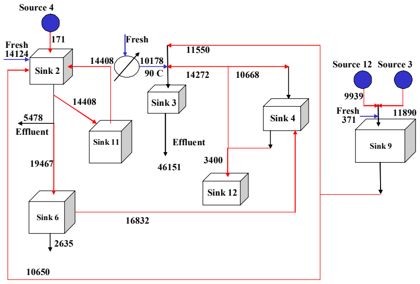

Figure 3: Optimal solution for 60% reduction in fresh water demand

However, if viable projects (with high savings and low total investments) could be identified with this stream included, this would make a strong case for inter process integration rather than focus on a single process. In addition, temperatures of certain sources and sinks were varied (as represented by Equations 5 and 6) resulting in an "interception". Selection of these intercepted sources was based on incorporating process constraints. For instance, sources with city water were considered rather than effluent streams. Several intermediate intercepted temperatures were also considered. Once the total fresh water and intercepted temperatures were fixed and the number of sources and sinks being considered was finalized, this case became a mixed integer linear program. A global solution was obtained for each run. This led to a "pareto" of results of lowest cost solutions for each % reduction in total fresh water demand. The optimization programs were solved using LINGO8$^{\mathrm{TM}}$. An example network at 60% reduction is given in Figure 3. In addition, benefit matrices can be created from the optimization. Figure 4 divides the X-Y space into four quadrants. The "best" projects (which may not be the most optimal!) lie in the "highly desirable" quadrants (these projects demonstrate high savings with low investment requirements resulting in high IRR and NPV. The "implementation desirable" quadrant includes those

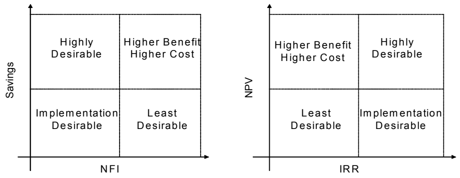

Figure 4: Benefits Matrix

projects that have low capital requirements but generate low savings. These are typically desirable especially if capital constraints are stringent.

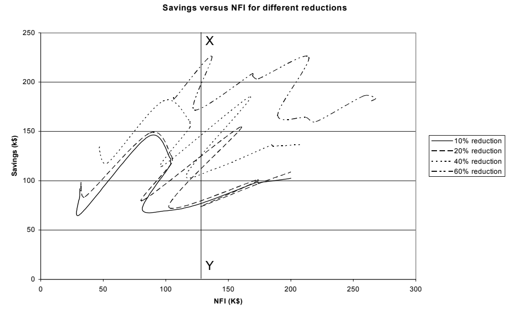

Figure 5: Savings versus new fixed investment (NFI) for different reductions in fresh water

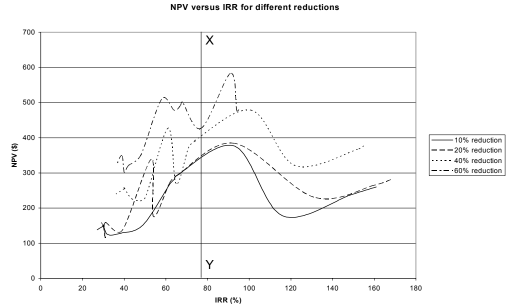

Figure 6: Net Present Value (NPV) versus internal rate of return (IRR) for different reductions in fresh water

The "higher benefit higher cost" quadrant corresponds to those projects that need decisions on willingness to spend more capital to get higher savings. Figures 5 and 6 summarize projects at different overall fresh water reductions. Each line corresponds to various projects at the same targeted fresh water reduction. Each project is a case defined using specific criteria such as the sources considered, intermediate temperatures etc. As this reduction % increases, the NFI increases as well. If a straight line XY is drawn on either plot, one can determine the projects with maximum savings at a given NFI or identify those projects that have the highest NPV at a given IRR. It may be noted that multiple projects may have the same savings at the same NFI for a given % reduction in fresh water flow (Refer Figure 5). This multiplicity can be exploited in the selection of the final network. The central message of this analysis is that there are different solution options generated by this approach thus allowing the user to consider different networks to get to the same target of fresh water reduction.

Conclusions

This paper has introduced optimization of water networks with temperature constraints being granted primacy instead of the traditional approach of focusing on concentration constraints. The solution strategy allows determination of a range of possible networks with different savings and investment requirements. This problem is highly relevant to industry as temperature constraints are easier to handle than concentration constraints (heat exchangers are more prevalent, easier to install and operate and typically cheaper than separation equipment). Besides, energy savings are typically higher as the unit cost of steam/refrigerant is higher than that of water. Several projects were developed at the Solutia Springfield, MA site based on this analysis.

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