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APPLY PROCESS INTEGRATION TO OPTIMIZE YOUR PLANT

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ABSTRACT

In this work, process integration is introduced and illustrated through examples in a new unique framework that assists process engineers and researchers in industry and academia to follow and apply in their practical projects and work. Mathematical optimization could be used to complement this approach. This approach allows engineers to explore and evaluate several opportunities to enhance their design and reduce the overall cost of the process.

Keywords: *process integration, optimization, process simplification, function analysis*

الملخص

العمل يتكلم عن و يقدم التصميم المتكامل للمصانع الكيميائية بطريقة جديدة تساعد العاملين في المجال في الصناعة و الجامعات بتطبيقها في مشاريعهم و أعمالهم الصناعية. الطريقة تعتمد على تحديد الخطوات التى يجب عملها. عدة أمثلة سوف يتم عرضها لتوضيح الفوائد للطريقة. ممكن استخدام البرمجة الرياضية للمساعدة فى تعريف أفضل التصاميم الهندسية للمصانع الكيميائية.

INTRODUCTION

Process development goes through several stages starting from bench scale experiments and ending with a complete detailed engineering package that is ready to be handled to an engineering company for construction and start up. Each process involves several units/equipment that interact with each other and the cost of the process depends on how well the resources within the process or the plant have been identified and utilized. To better utilize the resources available in the process or the plant, process design engineers and researchers have introduced the concept of process integration and have done extensive research in this area. Process integration framework includes process measurement, synthesis, analysis, optimization, and control. Process integration looks at the process as a whole, maximizes usage of existing resources, and optimizes the process. Several optimal solutions can be generated based on fundamental understanding of the process. This is a very important characteristic of process integration since objectives change from one process to another.

Cost reduction, technology selection, yield enhancement, waste minimization, process debottlenecking, and process simplification can be systematically addressed through process integration.

PROCESS INTEGRATION

Process integration relies on using fundamental principles of engineering and science to assemble the “building blocks” correctly that is to select and design them correctly as individual components. The “building blocks” could be any unit operation or equipment used or available for usage in the process. Fundamental understanding of the process is used to understand the big-picture of mass and energy flow in the process, that is to identify the target to be attained by process integration.

The target could be minimum wastewater discharge [Hamad et al., 1998], [El-Halwagi, 1997]; [Doyle and Smith, 1997]; [Wang and Smith, 1994], minimum heating and cooling utilities [Linnhoff, 1994], reactor attainable region [Biegler et al, 1997], minimum waste interception/separation cost [El-Halwagi 1997], etc. Whence the target has been identified, engineers work with the appropriate level of details including data measurement and collection to realize their process target.

Process integration is a comprehensive approach that includes two dimensions: mass integration and energy integration. Mass integration is the optimal generation, allocation, separation and routing of species throughout the chemical process. Mass is the core of the chemical process and it sets the directionality of the process. Several graphical mass integration tools can be utilized to provide insightful analysis, reduce the size of the problem, and develop optimal solutions.

Energy integration identifies the optimal utility usage in the chemical process. Energy integration analysis can be limited to thermal pinch so as to minimize heating/cooling utilities or can be more comprehensive by incorporating power and fuel. There is a complementary relationship between mass integration and energy integration. Mass integration tackles energy indirectly and identifies optimal tasks or strategies to be performed by energy integration.

Functional-Based Approach (How?)

To progress from raw material to product, processes consist of unit operations or equipment that are designed and used to perform specific task(s) or function(s) (tasks and functions are used interchangeably in this paper). Hence, in order to identify process integration opportunities and apply process integration techniques, the tasks/functions that need to be performed in the process should be identified ahead of any detailed design. This is the most important stage in process integration. Overall process functions are developed in three stages:

Stage 1: The primary functions are defined based on overall project or process objectives. For example, if the reactor effluent consists of P(product), R(raw material), and W(waste), then some of the potential primary functions would be:

Reduce W	Separate P from R and W
Separate R from W	Recycle R

It is very important here to realize that each function is represented linguistically by a verb and a known. This will make it much easier for design engineers later in the development stages to combine or eliminate functions and to find the proper alternatives to accomplish the desired function(s).

Stage 2: As we start to implement the functions identified in stage 1, other functions will come up. Examples include heating and cooling of streams, increasing pressure of streams, non-ideal separation, recovery of waste, etc.

Stage 3: This stage involves new functions that could be identified because of safety, control, process integration opportunities, and others.

To optimize the system via process integration, the following questions need to be addressed for each function: Why? How? When? The Functional Analysis System Techniques (FAST) diagram can present the answers to these questions graphically. The FAST diagram was introduced in 1965 (Snodgrass and Kasi, 1986).

Functional Analysis Techniques Diagram (FAST)

Functions can be used to help in defining the necessary steps that are needed to accomplish the objectives of process development and synthesis. Functions could be primary, secondary, or supportive. Primary functions are those functions that are necessary from the viewpoint of "big picture" analysis to go from raw material to product (Gopalakrishnan et al., 1997). Mainly these functions are related to reaction and separation steps pertaining toward product generation and separation. Secondary functions are those occur at the same time as the primary function do. They are divided into three categories. First, "unwanted" functions such as waste generation. Second, "wanted" functions such as product recovery. Third, "un-harmful" functions such as material holding. Supportive functions could represent heating, cooling, increasing pressure, etc. The following figure shows a generic representation of the Process FAST diagram. In this figure, the FAST diagram addresses process objectives and development steps.

In this diagram, Figure (1), primary functions establish the critical path functions to go from raw materials to the final product. The functions from left to right should answer the question why? The functions from right to left should answer the question how? The functions that are connected vertically occur simultaneously or caused by each another. The two vertical lines, one right after "feed raw material" and the other right before "final product," represent the boundaries for the scope of the process.

Illustrative Example: Ethyl Chloride Process (El-Halwagi et al, 1996; Hamad, 1997)

In this process, raw materials (ethanol and HCl) are fed to the reactor. The gaseous product of the reactor is scrubbed twice before it goes to finishing and sales. The wastewater streams generated from the scrubbers are recycled to the reactor. Another wastewater stream is generated from the reactor. Figures (2 & 3) show the process for ethyl chloride production and the FAST diagram for this process.

PROCESS INTEGRATION TECHNIQUES

There are several process integration techniques and tools that were developed in the last two decades. In this section, some process integration techniques will be discussed briefly.

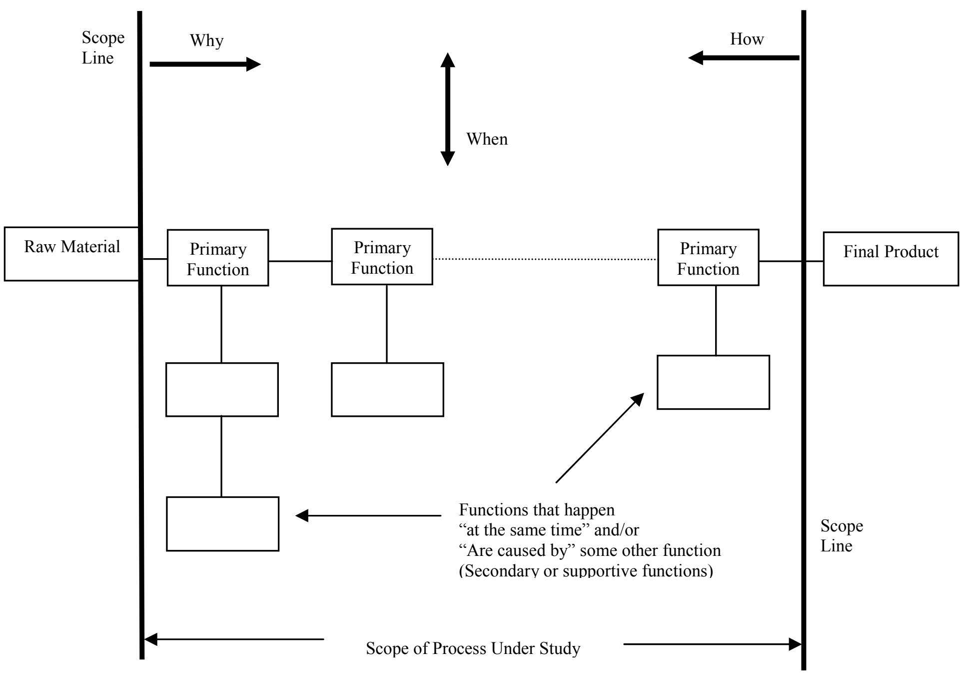

Figure 1: Process Functional Analysis System Techniques Diagram

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Process Simplification

Process simplification refers to reducing number of processing steps (unit operations) in the process for the purpose of reducing the overall cost of the process. In some cases, minor cost differences could be sacrificed for a simpler process. The following is a procedure that could be followed to systematically arrive to a cost-effective simplified process.

1. Determine the overall objective of your process/project
2. Develop the FAST diagram
3. Assign a cost to each function (primary, secondary, and supportive)
4. Apply process simplification principles to generate alternatives and reduce the cost.

   The following is a list of some of these principles.

   a. Is it necessary to perform all these functions?
   b. Can we eliminate the "unwanted" secondary functions?
   c. Is there another technology that can do the same function at a lower cost?
   d. Can we extend the operating zone of existing units to perform more than one function and hence eliminate some equipment? (Gopalakrishnan et al., 1997)
   e. Can we use new technology that can do more than one function and hence reduce the number of equipment in the process? (Gopalakrishnan et al., 1997)
   f. How can we run continuously or batch to maximize the usage of our existing resources?
   g. Are there any other resources exist in the plant?

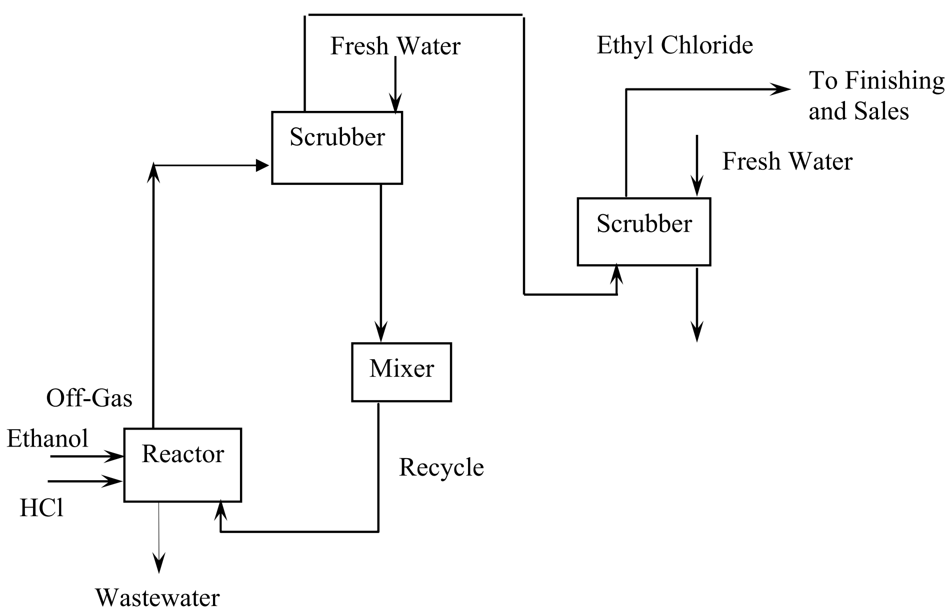

Figure 2: Ethyl Chloride Process

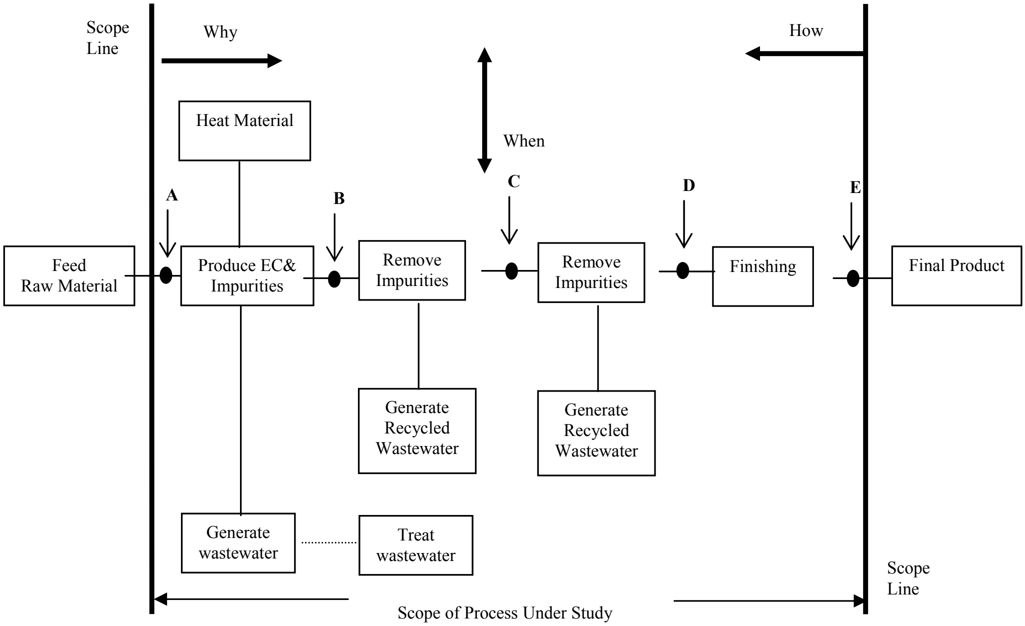

Figure 3: Process Functional Analysis System Techniques Diagram

Mass Allocation and Interception/Separation

Mass is the core of the chemical process and it sets the direction of process development and integration. Several graphical techniques could be used to foster the understanding of mass flow in the process and assist in developing alternative solutions. Some of these techniques include: mass pinch (El-Halwagi, 1997), path diagram (El-Halwagi, 1997; Hamad, 1997; Hamad et al, 1998), source-sink mapping diagram, (El-Halwagi, 1997; Hamad, 1997; Hamad et al, 1998), and water pinch (Wang and Smith, 1994).

Integration of Path Diagram and Process Simplification and Functional Analysis

The path diagram is a graphical tool that provides a global picture of the mass flow throughout the process without having to deal with complicated process flow diagrams. The following is a generic configuration of the path diagram:

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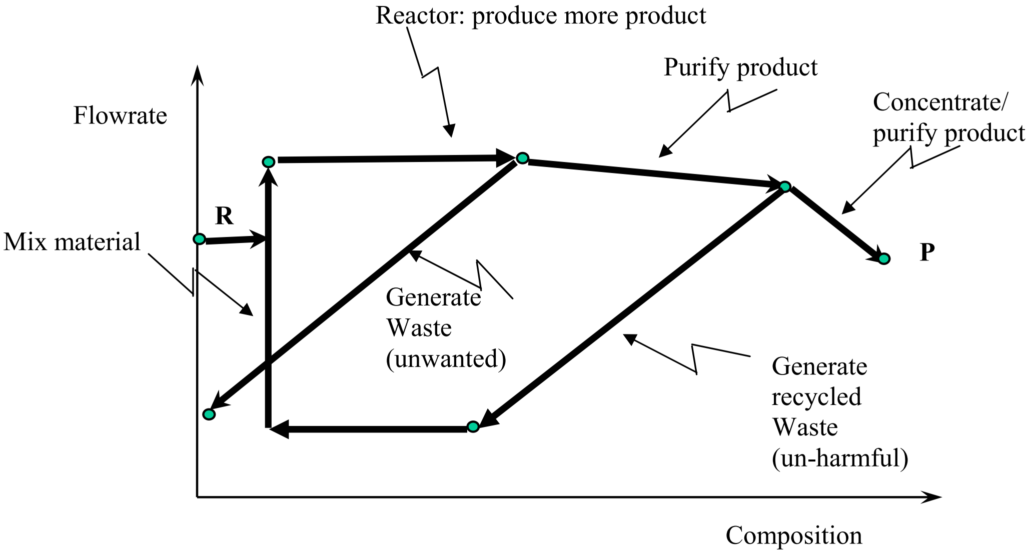

Figure 4: Generic Path Diagram

Each node on the path diagram represents a stream and each line segment between connected nodes represents a function that was performed by specific equipment. The overall objective of the process is to move from the node of the "raw material," point R, to the node of the final product, point P, with minimum number of "equipment" while being cost-effective. From this representation of the path diagram, the FAST diagram can easily be developed and several alternatives can be explored. A major advantage of this presentation is that composition and flowrates are represented simultaneously with functions. It is easier now to:

- Identify new technologies;
- Extend and modify operating zones of existing technologies;
- Explore mass integration opportunities (interception, allocation, etc.); and
- Develop set of alternative solution.

Thermal Pinch Analysis: More Than Heating and Cooling Minimization Tool

Thermal pinch is a pioneer tool in process integration. It was developed to minimize heating and cooling utilities (Linnhoff and Hindmarsh, 1983; Linnhoff, 1994). There has been extensive work in this area to better utilize the thermal pinch analysis. Thermal pinch diagram is a very useful tool not merely to optimize heating and cooling utilities in the process, but also to provide insightful analysis to enhance design and reduce cost of the process. The location of the hot and cold streams on the pinch diagram can provide engineers with several insights about their process. Examples include:

- Streams could move up or down on the pinch diagram by changing their pressure to maximize heat exchange between the cold and hot composite streams. The pinch diagram can identify the streams that could be modified to enhance internal heat exchange in the process.
- The quantity and quality of "unused" heat in the process will be determined on the pinch diagram. How can we use this heat to enhance the performance of our process?
- Can we increase the scope of the pinch analysis to include other parts of the process to reduce heating and cooling requirements in the plant?

Case Study 1: Process Simplification and Waste Minimization

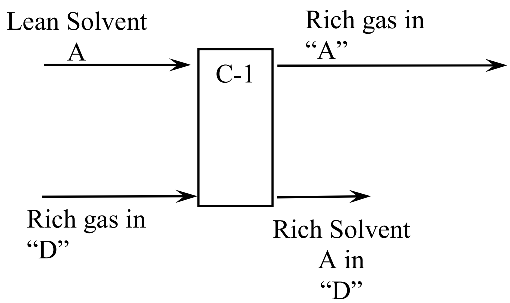

Figure 5: Case Study 1, Process Simplification and Waste Reduction

In this case study, solvent A is used to absorb species D from a gaseous stream in column C-1. However, the gas stream stripped some of the solvent. The task of the design engineers was to recover the "lost solvent" so that the gas stream could be emitted to the atmosphere. Since A is very soluble in water, they decided to use another absorber to recover A followed by a distillation column to separate A from the water so that both species could be recycled and used in the process.

Process Integration Solution

The principles of process integration were applied to explore other opportunities to recover solvent A in a simpler and more cost effective way. Replacing solvent A was not recommended since this solvent already exists in the process. Strategies of mass allocation and process simplification were utilized. The new solution indicated that no new equipment is needed and that we can extend the operating zones of other equipment that already exist in the process to achieve our goal. There is another distillation column, C-4, exists in the plant used to separate A, D, and water, with the help of a decanter, to three pure components. The solution was to extend the operating zone of column C-1 where we will feed solvent A to a lower stage and feed water to the top of the column. The liquid product is then fed to column

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C-4. In this solution, all generated wastewater from C-4 is recycled to column C-1. Large quantity of the water leaves the column with the gaseous stream. There is no need for the new two columns that were recommended earlier by the design engineers instead minor modifications were done to the existing columns C-1 and C-4 to accommodate the new tasks. The final solution is shown below.

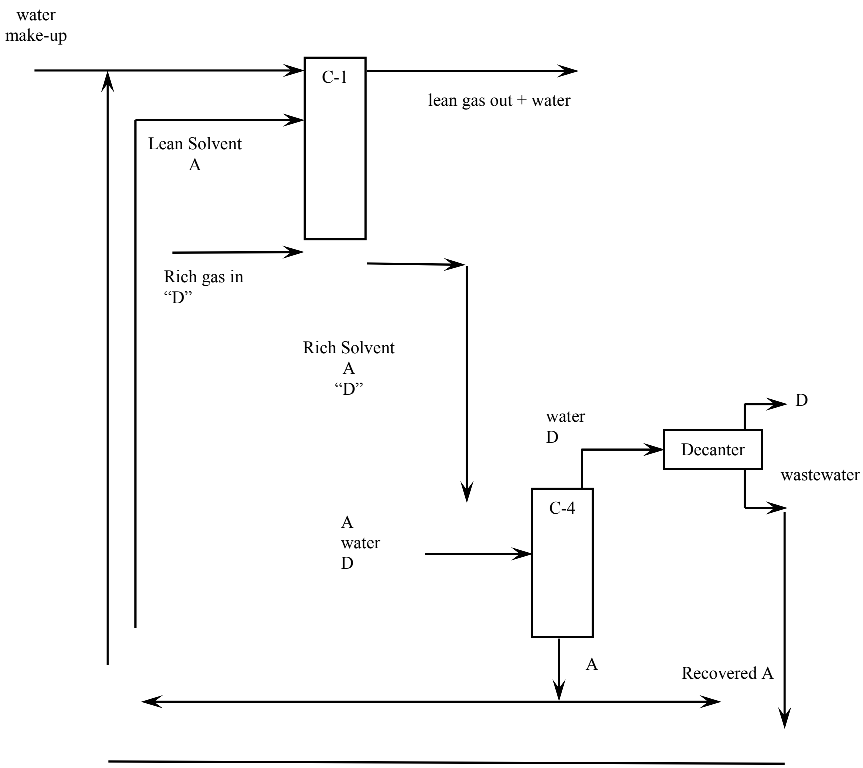

Figure 6: Optimal Solution of Case Study 1

Case Study 2: Insightful Thermal Pinch Analysis

This process consists of three distillation columns used to separate species X, Y, P, and W. The objective was to minimize the heating utility of the process. Since the three columns were running at three different pressures, the temperature differences among the columns were appreciable. The pressure was lowest in the first column and highest in the last column. The heaviest component was removed in the first column. Also, the columns could not be combined in any fashion because of difficulties in separation. Because the overhead temperature in the last column was much higher than the bottom temperature in the second column, design engineers decided to use the overhead of the last column to provide all the heat needed to boil the bottoms in the second column. An air cooler was chosen to finish the condensation of the overhead of the last column. Heating and cooling utilities were each reduced by 16 MMBtu/hr.

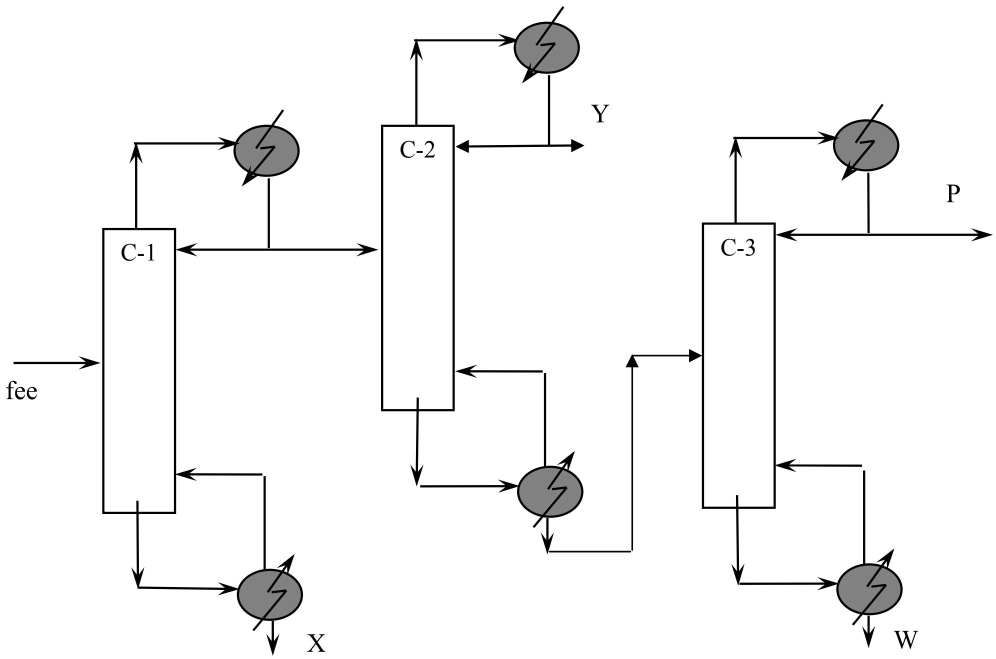

Figure 7: Case Study 2, Insightful Thermal Pinch Analysis

Process Integration Solution

To explore more opportunities to reduce heating utility in the process and to optimize the process, the pinch diagram for this process was developed, as shown below.

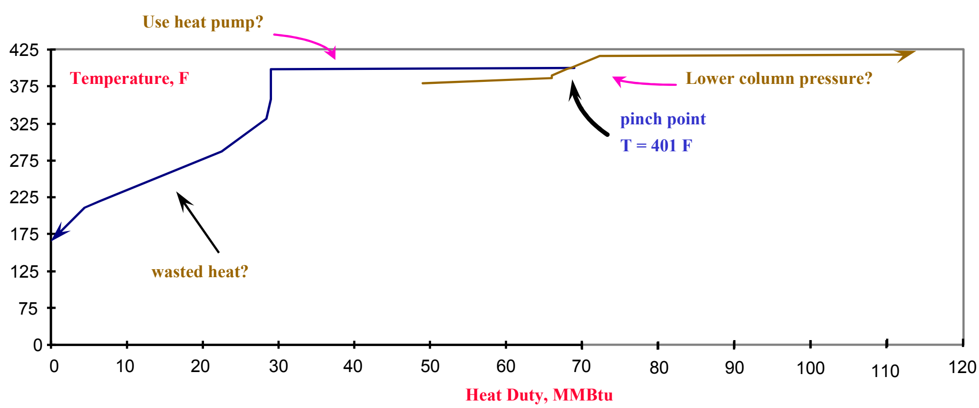

Figure 8: Pinch Diagram for Case Study 2

The following insights are drawn from the above pinch diagram:

1. The maximum internal heat exchange for the current design is around 20 MMBtu
2. If the pressure of the first column is reduced, the internal heat exchange can increase by approximately 4 MMBtu/hr
3. A heat pump could be used to integrate the overhead and bottoms of the last column
4. There is heat wasted in the process. Where can we use this heat? We could use it to preheat some of the feeds to the columns, heat boiler feed water, or for any other heating purposes in the plant
5. Can we find another heating source in the plant to accomplish some of the heating tasks for this process?

Here, the pinch analysis is utilized to better understand the global potential opportunities exist in the process. More opportunities could be added if the scope of the pinch is expanded to include other parts of the plant. In addition, considering fuel and power of the plant could have direct impact on these opportunities. Whence all potential opportunities are explored, then detailed economical analysis should be performed. Other design comparison criteria such as safety, control, operability, etc. would come after the economical evaluation to support or suppress projects and ideas.

CONCLUSION

Process integration is a comprehensive and flexible approach aims at minimizing the cost of chemical processes by maximizing the usage of existing resources and opportunities in the process/plant. Process integration tackles all aspects of process design and development such as material, energy, emissions, operations, and safety. We presented a unique approach to process integration using the FAST diagram. Integration of FAST diagram, path diagram, and process simplification was illustrated. Examples of process integration were used to illustrate the practical effectiveness of this approach. With this approach, simple mathematical analysis and optimization are needed. The dimensions of any chemical process (reaction, separation, utility) can be optimized by applying process integration techniques.

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