EDUCATIONAL TOOLS FOR POLLUTION PREVENTION THROUGH PROCESS INTEGRATION

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With today's increasingly stringent environmental regulations, there is a growing need for cost- and energy-efficient pollution prevention. This paper is based on a senior-level/first-year graduate-level course taught at Auburn University that provides a unique framework for teaching systematic techniques for addressing pollution prevention in the process industries while reconciling environmental issues with other plant objectives such as cost effectiveness, yield enhancement, resource conservation, and energy reduction. (Similar aspects of the course have also been taught at the University of Virginia.)

The overall philosophy, techniques, and tools presented in the course are rooted in fundamental engineering principles and process integration. This approach is significantly different from traditional teaching of pollution prevention where the environmental problem is addressed with a narrow mandate focusing on small segments or streams of the process and experience and subjective opinion are then used to tackle the problem.

This traditional teaching approach presents a number of problems.

- *There is a bias toward end-of-the-pipe solutions rather than understanding and solving the problem fundamentally.*
- *The pollution problem can inadvertently be transferred from one medium to another (e.g., from air to water).*
- *Proposed solutions to the environmental problems lack the systematic nature that is the trademark of chemical engineering successes. Instead, the approaches taught to the students are typically based on hit-or-miss procedures or attempts to replicate other solutions regardless of the specific nature of each process.*
- *The solutions are, therefore, suboptimal, and result in higher costs and less actual reduction in pollution.*
- *Finally, there is limited opportunity for the students to understand and learn the broader lessons of what features of process designs cause pollution problems in the first place.*

This current state of affairs calls for a fundamental and generally applicable approach for teaching and addressing pollution prevention.

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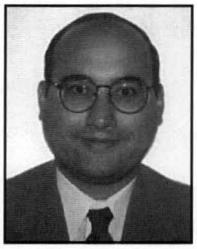

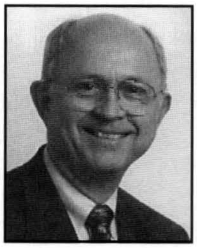

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PARADIGM SHIFT IN TEACHING POLLUTION PREVENTION

The authors have introduced and illustrated the use of a complete methodology for addressing pollution prevention and have transferred it to the classroom. It incorporates recent developments in integrated process design and is based on understanding the big picture first, dealing with details only after the important structural decisions have been made. The course has a number of key defining features:

- *It is based on the fundamentals of chemical engineering, process integration, thermodynamics, mathematics, and principles of problem decomposition.*
- *The students learn how to set robust performance targets for pollution prevention, yield improvement, energy integration, and cost effectiveness ahead of detailed design.*
- *Trade-offs are made at the targeting stage, allowing the students to avoid unnecessary design detail.*
- *Process synthesis methods and chemical engineering tools are then employed to systematically make the trade-offs and to realize the targeted performance.*
- *Throughout the course, extensive use is made of tools for representing complex process interactions in ways that are both rigorous and easy to interpret. These tools are illustrated with numerous industrial applications.*

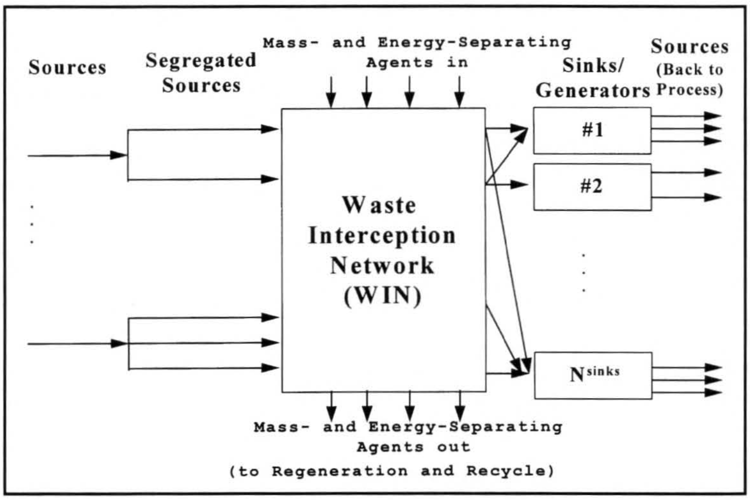

Figure 1. *Schematic representation of mass-integration strategies for pollution prevention: segregation, mixing, interception, recycle, and sink/generator manipulation.*[1,5,6]

WHAT IS PROCESS INTEGRATION?

A chemical process is an integrated system of interconnected units and streams, and it should be treated as such. Process integration is a holistic approach to process design, retrofitting, and operation and emphasizes the unity of the process. In light of the strong interaction among process units, streams, and objectives, process integration offers a unique framework for fundamental understanding of the global insights into the process, methodically determining its attainable performance targets and systematically making decisions leading to the realization of those targets. Process integration has recently been reviewed in various educational literature.[e.g.,1,2]

Two key branches of process integration have been developed: mass integration and energy integration. Energy integration is a systematic methodology that provides fundamental understanding of energy utilization within the process and employs this understanding for identifying energy targets and optimizing heat-recovery and energy-utility systems. Numerous articles on energy integration have been published.[e.g.,3,4] Of particular importance are the thermal-pinch techniques that can be used to identify minimum heating and cooling utility requirements for a process.

On the other hand, mass integration[1,5,6] is a systematic methodology that provides fundamental understanding of the global flow of mass within the process and employs this understanding for identifying performance targets and optimizing the generation and routing of species throughout the process. Mass-allocation objectives such as pollution prevention are at the heart of mass integration. Mass integration is more general and more involved than energy integration, and because of the overriding mass objectives of most processes, mass integration can potentially provide much stronger impact on the process than can energy integration.

Both integration branches are compatible. Mass integration coupled with energy integration provides a systematic framework for understanding the big picture of the process, identifying performance targets, and developing solutions for improving process efficiency, including pollution prevention. The core of the course is dedicated to mass-integration techniques.

MASS INTEGRATION TECHNIQUES FOR POLLUTION PREVENTION

Mass integration is based on fundamental principles of chemical engineering combined with system analysis using graphical and optimization-based tools. The first step in conducting mass integration is development of a global mass allocation representation of the whole process from a species viewpoint, as shown in Figure 1. For each targeted species (*e.g.,* each pollutant) there are sources (streams that carry the species) and process sinks (units that can accept the species).

Process sinks include reactors, heaters/coolers, biotreatment facilities, and discharge media. Streams leaving the sinks become, in turn, sources. Therefore, sinks are also generators of the targeted species. Each sink/generator may be manipulated via design and/or operating changes to affect the flowrate and composition of what each sink/generator accepts and discharges.

In general, sources must be prepared for the sinks through segregation and separation via a waste-interception network (WIN). Effective pollution prevention can be achieved by a combination of stream segregation, mixing, interception, recycle from sources to sinks (with or without interception), and sink/generator manipulation. Therefore, issues such as source reduction and recycle/reuse can be addressed simultaneously. The following sections summarize these concepts.

Segregation

Segregation simply refers to avoiding the mixing of streams. In many cases, segregating waste streams at the source renders several streams environmentally acceptable and hence reduces the pollution-prevention cost. Furthermore, segregating streams with different compositions avoids unnecessary dilution of streams. This reduces the cost of removing the pollutant from the more concentrated streams. It may also provide composition levels that allow the streams to be recycled directly to process units.

Recycle

Recycle refers to the utilization of a pollutant-laden stream (a source) in a process unit (a sink). Each sink has a number of constraints on the characteristics (*e.g.,* flowrate and composition) of feed that it can process. If a source satisfies these constraints it may be directly recycled to or reused in the sink. But if the source violates these constraints, segregation, mixing, and/or interception may be used to prepare the stream for recycle.

Interception

Interception denotes the utilization of separation unit operations to adjust the composition of the pollutant-laden streams to make them acceptable for sinks. These separations may be induced by the use of mass-separating agents (MSAs) and/or energy separating agents (ESAs). The design of these interception networks can be handled using a process integration technique referred to as the mass-pinch analysis.[7-10]

Sink/generator manipulation

Sink/generator manipulation involves design or operating changes that alter the flowrate or composition of pollutant-laden streams entering or leaving the process units.

TABLE 1
Course Outline

Overview of Process Integration and Pollution Prevention *(2 lectures)*

- Extracting global insights from a flowsheet
- Branches of process integration
- Pollution prevention hierarchy

The Role of Simulation in Preventing Pollution *(1 lecture)*

- Process simulation versus process synthesis
- Basic modeling concepts

Mass Pinch Analysis *(6 lectures)*

- Development of waste composite representations
- Development of lean composite streams
- Simultaneous screening of mass-separating agents
- Graphical mass-pinch analysis
- Optimization-based mass-pinch analysis

Graphical Techniques for Mass Integration *(6 lectures)*

- Segregation, mixing, recycle, interception, and unit manipulation
- Establishing pollution-prevention targets from a breadth analysis
- Waste source-sink mapping analysis
- Systematic development of solutions to meet the target
- Integration of pollution prevention with other process objectives

Energy Effects in Preventing Pollution *(5 lectures)*

- Thermal-pinch analysis
- Combined heat and mass exchange networks
- Energy-induced systems

Integration of Process Synthesis and Process Simulations *(3 lectures)*

- Mathematical programming and optimization
- Path diagrams for tracking pollutants
- Integration of path and pinch diagrams

Reactive Systems *(5 lectures)*

- Establishing thermodynamic targets for reactive systems
- Reactive mass-pinch analysis
- Synthesis of environmentally acceptable reactions
- Design of benign species

These measures include temperature/pressure changes, unit replacement, catalyst alteration, feedstock substitution, reaction-path changes, reaction system modification, and solvent substitution.

STRUCTURE OF THE COURSE

The course was first offered at Auburn University in the fall of 1990 as part of the senior-level design sequence and graduate-level electives. Since then, the course has been refined and updated. On the average, it is attended by about seventy-five students per year. Table 1 shows the course outline.

A related course is also offered at the University of Virginia. The syllabus for that course is available in a recent *CEE* article.[2]

EXAMPLES OF TERM PROJECTS

In order to illustrate the applicability of the techniques taught in the course, the students are required to address a pollution prevention problem in an integrated manner. The projects are chosen from literature or from actual operating facilities. Recent projects include

- Water reduction in a pulp and paper mill
- Desulfurization in a coal-processing facility
- Metal removal from a copper-etching process
- Reduction of VOC emissions for a vinyl-chloride process
- Sweetening of coke-oven gas facility
- Dephenolization in an oil refinery
- Reduction of solvent loss from a coating facility
- Benzene removal in a polymer facility

RESOURCE MATERIAL

The main reference for the course is the textbook *Pollution Prevention through Process Integration: Systematic Design Tools*.[1] Other useful books have also been recently published.[11,12] There are also many archival papers that provide design techniques and case studies that can be used as term projects for the course (see References 1, 2, and 5 for a citation of available literature).

CONCLUDING REMARKS

The course provides a unique approach to pollution prevention—one that is rooted in fundamentals, is generally applicable, and is not left to subjective opinion and arbitrary solutions. It emphasizes the unique role of chemical engineering in preventing pollution. The course provides a thorough and comprehensive analysis of both mass and energy flows in processes and results not only in pollution prevention but also in yield improvement, energy use reduction, solvent recovery, and cost reduction. These are all compatible goals when undertaken properly and when the integrated nature of the process is well understood.

This paper is based on a senior-level/first-year graduate-level course . . . that provides a unique framework for teaching systematic techniques for addressing pollution prevention in the process industries.

Due to its systematic nature, the course is well suited for educational purposes and it also prepares the students to tackle real problems after graduation. This has been validated by the feedback provided by hundreds of undergraduate and graduate students who took the course and later indicated that it had a major impact on their first industrial job.

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