



SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY
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SCHOOL OF BIO AND CHEMICAL ENGINEERING

DEPARTMENT OF CHEMICAL ENGINEERING

UNIT – I – Process Engineering – SCHA1702

A framework is introduced typically for developing new products, together with innovation maps to help identify the connections between technological inventions and the voice of the customer. Special emphasis is placed on the growing importance of protecting the environment and ensuring safe and reliable chemical products, as well as manufacturing facilities, considerations that are prominent in the minds of product and process design teams.

1 . 1 Product- And Technology-Development Framework

The Stage-GateTM Technology-Development Process (SGTDPTM) is comprised of three stages : technology scoping, technology assessment, and technology transfer. Technology scoping is a relatively inexpensive stage of brief duration involving idea generation , literature searching, and evaluating alternative ways for conducting the technology-development project. The technology assessment stage is more extensive, as it is designed to demonstrate technical feasibility; that is, to show that a new technology functions properly and is worthy of further attention. The technology transfer stage usually involves a full experimental and/or modelling effort to advance the technology and justify the identification of potential applications, products, and/or new manufacturing processes. During this latter stage, potential new products may be identified and defined, with preliminary market and business analyses conducted. Often, connections to potential business partners are identified and explored to learn their potential interests in technology transfer. When technology transfer takes place, ideally it is connected to a product-development effort, and is most likely to be transferred to the concept or feasibility stages of the Stage-GateTM Product-Development Process (SGPDP). Often the new technologies, while successfully demonstrated, are ahead of their time, not finding a place in the market until long after they are developed. In fact, some new technologies never reach the market, or quickly fail in the marketplace, for reasons including a lack of customer acceptance, business infeasibility, and obsolescence relative to other new technologies. The network PC falls in the category of failed customer acceptance; no one wants a terminal when he or she can have a full-blown PC. Some new technologies result in a single product or a family of products having a wide range of applications. In the latter case, the terminology technology platform is often used. Examples include the Internet, polymers, wireless, lighting, and display technologies, and many others.

1.2 Innovation Map And Classes Of Chemical Products

Innovation map (Widagdo, 2006), which was developed to help identify the connections between various technological inventions (materials, process/manufacturing, and product technologies) and the voice of the customer (market or customer needs). It is these connections, or intersections in space, that present new product opportunities. The innovation map helps to connect the technology developers to the product developers and their customers (end users and business-to-business customers). It can also be used to identify product platforms or families, and strategies to protect both the technological inventions and the product innovations.

Invention and Innovation. These terms are often used interchangeably in a casual discussion and presentation. More formally, invention refers to a scientific discovery with a clear technical advantage over the current state-of-the-art, and is generally protected by a patent. Innovation, the favorite word of Bill Gates when he discusses products produced by Microsoft, is, on the other hand, the creation of business/economic value through differentiations (technical, business, sales, marketing, customer service, product, etc.). The transformation of these differentiations into customer values, satisfying a customer-value proposition, discussed below, is the key for successful new product development. Product differentiation is important to differentiate internally a family of product offerings and to differentiate their products from those of the competition.

1.3 Innovation Map

A product-development effort can be technology or market driven. A market-driven, new product development starts with a known market or customer need for a solution. A good example of a market-driven technology is Scotch¹ MagicTM Tape of the 3M Company. In 1959, when the Xerox plain-paper photocopier using xerography began replacing the Photostat copier, which produced a negative print, a new era began. Consumers could now paste up a sheet to be copied, using pieces cut from various sources. The pieces could be pasted onto the sheet or fastened to the sheet with cellophane tape. However, the Xerox copy would clearly show the outline of the piece if pasted or a smudged surface where cellophane tape was used. Scotch¹ MagicTM Tape, with its frosty matte finish and absence of acetate that reflects light, came to the rescue. This tape was invisible on the Xerox copy. On the other hand, a technology-driven, new product development begins with a technological invention, involving

materials, process/manufacturing, and/or product technologies. Such an invention was the PC (personal computer), whose future was predicted in 1962 by John W. Mauchly, who in 1944 at the University of Pennsylvania, with J. Presper Eckert, designed the ENIAC, the first general-purpose, electronic, digital computer. At that time, the future need for PCs was predicted by very few prognosticators. In either case (market driven or technology driven), it is necessary to match the market/customer needs with the technological invention. The successful match creates product innovation, with the innovation map providing the link-ages between the technology and market voices. These linkages, while straightforward to create, are often overlooked outside of the business world, as the technology and market voices are often owned by the different organizations.

For example, in many companies, the technology voice is owned by the Technology-Development (R&D) organization while the market voice is owned by the Business-Development (Sales/Marketing) organization, with communication gaps created inadvertently between these organizations. The creation of the innovation map helps to bridge these gaps. Clearly, the R&D organization concentrates on technical differentiations, such as higher manufacturing speeds, lower evaporation rates, higher melting points, etc. However, the technical staff often focuses on these attributes without translating them adequately into customer values; that is, without a focus on the customer-value proposition. For example, isophthalic acid was first produced in 1955 as a highly touted replacement for the well-established product.

1.4 Project Charter And New Technologies

With a pipeline for new product development in place, as promising ideas are generated, design teams are formulated, which begin their work by creating a project charter.

1.4.1 Project Charter

A project charter is the starting point for a product-development effort. Its key elements are specific goals, a project scope, deliverables, and a time line. When developing a project charter, design teams often seek to follow the SMART principle; that is, to focus on specific, measurable, agreed-upon, realistic, and time-based aspects of the product design. By specific, it is implied that the charter is well defined and clear to persons with a basic knowledge of the project. The term measurable implies that well-recognized, clear indicators are available to denote when the project objectives have been achieved. By agreed-upon, it is implied

that all of the stakeholders are in agreement with the goals of the project. The term realistic implies that these goals can be achieved using available knowledge, time, and resources. And, finally, the term time-based implies that the datelines for completion of the overall project and its stages are sound.

The identification of specific goals, that is, specific targets, is very important to prevent so-called project scope creep. Often, these goals are expressed by stating the objectives of the project or, alternatively, by posing several questions to be answered during the course of the project. The project scope defines the boundary of the project. It is helpful to classify its associated elements as in-scope or out-of-scope using an in-scope and out-of-scope exercise. The SGPDP consists of several stages, between which gate reviews are conducted involving key stakeholders and decision makers from business, technical, manufacturing, supply-chain, and environmental, health, and safety organizations. At each gate review, a decision is made to either: (1) advance the design project to the next stage, (2) retain the design project at the current stage until pending critical issues are resolved, or (3) cancel the design project when a need is no longer recognized, or when roadblocks have been encountered that render the project infeasible.

To advance from stage to stage, a product-development project must pass the gate reviews; that is, receive passing grades. Each gate is intended to reduce the risk by verifying the manufacturability and matching the size of the opportunity and product features and performance to the customer needs. To facilitate the reviews, several tasks are designed to be accomplished in each stage. The gate reviews serve to check and verify that key questions have been answered satisfactorily before the design team is permitted. The major drawback of the SGPDP occurs when new development teams overemphasize the tasks and deliverables, losing sight of the critical issues in ensuring the success of their projects. To discourage this, in recent years many companies, including Procter & Gamble, Caterpillar, and Rohm & Haas, have modified the SGPDP to focus more on the critical issues in an outer layer, with the tasks and deliverables used to resolve the critical issues.

1.4.2 Concept Stage

The concept stage, being first in the Stage GateTM Product-Development Process, primarily serves as the business and product definition step. During this stage, an extensive investigation is carried out to define the product and to verify the attractiveness of the product prior to committing significant funds. When building an entirely new product family, this stage involves an extensive market study to define, not only the market opportunity, but also the market segment(s) and customer

needs. And consequently, the latter becomes the basis for developing the new product concepts. For new product extensions in an existing market, although the market segment(s) and customer needs are generally known, a careful verification of market viability and product strategy, as they relate to customer needs, is still required. This often applies for new basic chemical products when the variations in chemical structure, properties, and raw materials are small. In general, the goals of the concept stage are twofold: to (1) define the product and (2) build the business case. Note that in building the business case, a market opportunity assessment needs to be conducted. Because resources to obtain these data are usually not readily available in the public domain, it is recommended that students work with their librarians to obtain market data using the resources listed in the reference section and other sources. To accomplish the two goals, several tasks are recommended, including: carrying out a market assessment, determining customer requirements, determining product requirements, creating product concepts, and carrying out an opportunity assessment.

1.4.3 Market Assessment

A new product-development program often begins with a product or technology idea for which the new product-development team seeks to identify and analyze its value creation and value capture (Murray, 2007). For value creation, it aims to determine whether the idea would add significant value for customers, while for value capture, it aims to determine whether its inherent economic value can be captured in the face of competition. More specifically, when analyzing the value creation of a new idea, many questions are typically answered, including: (1) Who are the customers? (2) Who is likely to buy? (3) Who should be approached for sales? (4) Which markets should be considered? (5) Which customers are most likely to purchase? (6) Which product applications are most suitable for the technology idea? and (7) Which product applications are most valued by the customers?

1.4.4 Value Proposition

When carrying out a market assessment, it helps to prepare a value proposition, which is a clear, concise statement of the compelling attributes of the product(s) as viewed by the customers. These attributes usually are the features, functions, and benefits of the product(s), with a good value proposition normally describing the key product attributes for a group of customers. Note that the value proposition belongs to the products, not the underlying technologies that

enable the products. Also, the best product advertisements convey the value proposition in less than 30 seconds. They capture the audience; clearly convey the features, functions, and benefits to the audience; and entice the audience to purchase the products. For these reasons, considerable effort is expended in creating value-proposition statements.

1.4.5 Market Segmentation

Often a product can be sold in different markets or for different applications. For example, the Apple iPhoneTM can be marketed as a smart phone, a portable media player, or a personal digital assistant (PDA). While the iPhoneTM was designed to provide a combination of these three functions, the new product-development team should consider how to best capture the value of its product. To answer this question, several related questions should be addressed:

Which customers are willing and capable of paying the most?

Which customers would benefit most from the product features and functions?

Which applications are on the path to significant progress, that is, being developed most rapidly?

Which applications are served best by the product?

Note that the last two questions address the suitability of the technology that enabled the products, rather than customer needs for a specific product(s). Regardless, when addressing these questions, the success of a market segmentation depends on the customers' behaviour in the selected segment; more specifically, on the customers' ability to adopt a new product, where their needs may have been fully or partially fulfilled by an existing product.

A market is defined as a group of people (potential customers) who, as individuals or in collective organizations, have needs for products in a product category and who have the ability and willingness to purchase such products. While so-called end-use customers (consumers) benefit from the products, but not as profiteers, many companies and businesses buy products for resale, for direct use in production of other products, or for consumption in daily operation. As an example, office supplies are consumed daily by their producers.

Traditionally, markets are categorized by geography and demography. In demographic segmentation, groups of consumers are segmented by age, sex, ethnicity, income, education, occupation, family life cycle, family size, religion, or social class. Geographic segmentation classifies groups of consumers by subculture values, population size, population growth, population density, natural resources, natural terrain, etc.

Also, markets can be characterized by demand clusters having similar needs or patterns. Three typical demand clusters are:

Homogeneous demand, where the customers have uniform demands for products for similar reason(s). This commonly applies to products that satisfy basic needs such as food staples.

Clustered demand, where customer demands can be segmented into two or more distinct clusters. For example, cars are often segmented into luxury, basic, sport, or spacious (family-oriented) clusters.

Diffused demand, where customer preferences are varied. Here, product differentiations are more costly to establish and more difficult to communicate. For example, in the cosmetics market, companies are compelled to offer hundreds of shades of lipstick. Often, given such diffused demands, companies try to structure customer demands by developing market segments of moderate size.

Individuals or organizations with diverse product needs have heterogeneous needs or demand patterns. For these situations, market segmentation is the process of dividing a total market into market groups consisting of people having similar product needs; that is, forming clusters of needs. Its purpose is to create a market mix that more closely matches the needs of the individuals in the selected market segment(s). In summary, the resulting market segment(s) consist of individuals, groups, or organizations that share one or more characteristics leading to similar product needs.

When developing new products, having identified diverse market segments, the product-development team can either focus on a single market segment (finding the best match for its product with the needs of that segment) or design a product to satisfy the needs of multiple market segments. The latter is often achieved by: (1) offering a new product family or portfolio, with different products designed to match the needs of selected segments, or (2) designing a universal product that serves the needs of multiple market segments. One example of the latter is universal duct tapes that are effective in dry or humid climates. Note that market segmentation can also be used to organize the supply chain for this product.

1.4.6 Value-Chain Analysis

The capturing or realization of the potential economic value of a new product, in the face of competition, is crucial to the success of the new-product-development team. During the concept stage, the team needs answers to the following related questions:

Should we sell products and/or services? Note that Apple does both. New customers can subscribe to AT&T phone service through the iTunesTM application.

How should we protect the competitive advantage expressed in the value-proposition statement?

How far along the value chain should we go to capture the maximum value?

A value chain in a business is comprised of activities or functions in the creation and delivery of a product(s) to its end users. These are classified (Porter, 1998a,b) as primary, that is, directly needed in the production and delivery of the product(s), and secondary, that is, supporting activities not directly involved.

An example of a mobile-phone value chain for the wireless market consists of the entities chipset/infrastructure/platforms, handset makers, application developers, content providers, wireless operators, and retailers. For the chipset/infrastructure/platforms, the key players include Qualcomm, Intel, and Ericsson, who provide the chipset and the digital wireless technologies (e.g., BluetoothTM). The handset makers serve as integrators of the many elements of wireless devices, including the telecommunication processors and chipsets, housing designs, displays, keyboards, and user interfaces. Typical companies associated with this part of the value chain are Nokia, Samsung, LG Electronics, and NEC. The application developers and content providers provide application accessories and contents; for example, news application developers may work with news agencies, such as CNN or ESPN, to deliver content to the end users. Next in the value chain are the so-called network operators such as AT&T, Sprint, T-Mobile, and Verizon, which provide network wireless services. Finally, the last entity in the wireless value chain is the retailers, such as Best Buy and Circuit City, which sell the mobile phones to the end users—often serving as agents for the network operators included in the services they provide to their customers.

1.4.7 Customer Requirements

Until the last quarter of the 20th century, new-product development was generally viewed as the exclusive domain of scientists and engineers in the R&D organization. They sought to create

technological innovations that excite customers. These were transferred to other organizations, such as manufacturing, product development, and business development (see Figure 1.1), which carried them into the marketplace.

By the early 1980s, Japan had emerged as a world force in new-product development, having captured significant world market shares in industries as diverse as automotive, consumer electronics, and heavy manufacturing. Japanese companies and manufacturers placed heavy emphasis on quality, going beyond the simple methods for manufacturing-defect reduction taught by W. Edwards Deming, extending their quest for quality to the initial product design phase; that is, the concept stage (Deming, 1950). High atop their priority lists were studies of customer needs in every new product-development effort. To accomplish this, the Japanese developed the Quality Functional Deployment (QFD) methodology (Katz, 2004), where QFD begins with comprehensive lists of customer needs. Over time, the lists of needs and the process of obtaining them became known as the voice of the customer (VOC).

It has been traditional for the R&D organization to have little, if any, contact with customers. Rather, the business-development organization, with its marketing, sales, and technical-services groups, has maintained contacts and close working relationships with customers. As a result, marketing, sales, and technical service personnel have been added to product-development teams today to capture the VOC.

The process of obtaining the VOC often involves primary and secondary research. In secondary research, no customers are contacted and interviewed, but rather, general market requirements are collected through market studies and analyses. To distinguish this from primary research, it is said that secondary research provides the voice of the market (VOM), a more generic assessment of customer needs.

To a novice in product development, collecting the VOC might imply visiting and interviewing a few key customers. However, over the years, the science of listening, observing, interviewing, processing and analyzing customer needs, and converting them into useful product requirements has matured significantly. The first studies of the VOC, which continue to be highly regarded, were conducted and reported by Griffin and Hauser (1993). The principal steps of their process to obtain the VOC involve: (a) selecting customers, (b) preparing questionnaires, (c) conducting customer interviews, (d) processing and analyzing customer needs, and (e) translating the customer needs into product requirements. Next, these steps are introduced briefly, with readers referred to the chapter by Katz (2004) and the paper by Griffin and Hauser (1993) for further details. Selection of the customers is a critical step, often on par with determination of the sample size and population in a survey. In this selection, the contacts with current customers, as well as non-customers, are equally

important, with the latter often providing insights regarding their decisions not to purchase products. Similarly, contacts with major accounts, as well as small accounts, have comparable importance. Often, the latter are the least satisfied customers. It is also important to select customers associated with the various entities in the value chain for a product(s).

1.5 Product Requirements

Given a set of customer requirements, the product-development team seeks to express them as product requirements using a more technical language involving quantitative and measurable variables. The House of Quality (HOQ), also known as the Quality Function Deployment (QFD), relates the various requirements (customer, product, manufacturing) to one another. When first formulated, in the concept stage, the HOQ relates the customer requirements to the overall product requirements.

Often the customer requirements are categorized as fitness-to-standard (FTS) or new-unique-and-difficult (NUD). The former are basic requirements that must be satisfied for customers to purchase a product(s)—requirements that are related to satisfaction levels well known to the market, while for new-to-the-world products based on disruptive technologies, customers (early adopters) are able to knowingly and willingly accept substandard FTS performance. For instance, for the first digital cameras, early adopters were willing to accept poorer picture quality in exchange for the ability to transmit pictures over the Internet or manipulate images before printing.

Similarly, customers are rarely willing to pay more for the FTS features, while NUD requirements often attract customers, as well as higher prices, and are often available in limited supplies. Because the NUD requirements provide competitive advantages for companies, their fulfillment has priority in the concept stage, as illustrated by the Apple iPhoneTM.

HOQs are created to focus on different aspects of the Stage-GateTM Product-Development Process. For example, some HOQs are for overall systems, while others are for product subsystems or components. Yet others are for manufacturing subsystems and components. Hence, HOQs are often created, or extended, at different stages in the SGPD. To illustrate the creation of a first HOQ in the concept stage, consider the product design of a longer-lifetime incandescent light bulb. The lower rectangular matrix pairs the customer requirements in the first column with at least one quantitative technical requirement or parameter in the adjacent columns. For example, the customer requirement that the bulbs fit in lamps with shades, recess lamps, or tracking light fixtures

imposes a maximum operating temperature; that is, a technical variable with an upper bound to prevent fires. Similarly, the quality of light, warm or cool, imposes an operating temperature known as the color temperature. In other cases, the customer requirement translates directly into the technical requirement, for example, the lifetime.

At the top of the house, the interaction matrix shows the synergistic technical requirements or parameters—for example, the lifetime and color temperature. As introduced, (p) indicates that both variables increase or decrease; (i) indicates that when one variable increases, the other decreases, and vice versa; and a blank entry indicates no significant relationship between the variables. For the incandescent light bulb, the higher the color temperature, the higher the bulb temperature, and consequently, the shorter the lifetime. Thus, the (p) signals the need for a compromise between the color temperature and the lifetime/

1.6 Product Concepts

Having decided upon the technical requirements for the product(s), the product-development team begins to develop its new product concepts, that is, potential solutions that satisfy the NUD and FTS requirements. For complex products with many components, parallel development efforts, component by component, often lead to a collection of concepts for the combined product. Clearly, this approach is risky, as unanticipated interactions may be overlooked in the concept stage. For this reason, it is often necessary to defer judgment until a prototype can be created in the feasibility stage. In this respect, flexibility is crucial when deciding to carry a concept through to the feasibility stage. Ideally, a multifunctional product-development team creates the solution concepts, with the team comprised of multi-disciplinary personnel (Creveling et al., 2003), including:

Scientists and engineers who have developed the under-lying technologies likely to be used in the new product.

Development engineers in related fields.

Senior manufacturing engineers, such as those who developed previous generations of the product. Technical- and customer-service personnel who worked on previous generations of the product, or who have extensive experience in handling technical problems and customer concerns. Marketing and sales personnel. Supply-chain specialists.

Health, safety, environmental, and regulatory specialists.

This internally focused team is often complemented with technology-development partners from industry, academia, and/or the government. It may also include selected customers, with their levels of involvement dependent on the needs of the product-development projects. Usually, they serve as consultants rather than core members of the product-development team. When generating new solution concepts, the so-called Pugh matrix (Pugh, 1996), in which each solution concept (partial and complete) is judged against a reference solution, is useful for screening purposes. Given the reference solution, which is usually the best known in the market, each concept is evaluated against the reference solution and assigned a qualitative valuation of inferior (-), superior (+), or equal (0). Note that in refined variations of the valuation method, ratings such as (-) or (++) indicate different levels of superiority or inferiority. In most cases, solution concepts don't satisfy all of the requirements. When the violating requirements differ, combinations of the solution concepts are often attempted, with the combined concepts having a reduced number of violated requirements.

1.7 Opportunity Assessments

In the concept stage, product-development teams normally focus on assessing their product opportunities by carrying out preliminary product cost estimates and risk analyses. To proceed to the feasibility stage, their approximate cost estimates must be promising, with more accurate estimates compiled as the team proceeds from stage to stage through the SGPDP. For the design of basic chemical products, as shown in Chapter 13, the focus is usually on the profitability of the manufacturing processes, while for industrial and configured consumer products, as shown in Chapters 15 and 17, the estimates are more closely associated with the product selling prices and their mass production. Before recommending a sizable investment, it is crucial to assess the risks of not capturing the potential economic value, which involve estimating the economic value and the associated competition.

1.7.1 Porter Five-Forces Analysis

Competitive analysis commonly focuses on the competition forces within markets or industries. In 1979, Porter argued that in addition to the market competition force, there are four other forces to be considered: (1) the bargaining power of the suppliers, (2) the bargaining power of the customers, (3) the threat of new entrants, and (4) the threat of substitute products. To

these, a sixth force was added by critics of the Porter approach; that is, the bargaining power of other stakeholders such as government, shareholders, environmental agencies, etc.

The competition forces within the market influence and are influenced by the market growth rate, the number and diversity of competitors, the brand equity, the advertisement expense budget, and exit barriers. The bargaining power of the suppliers includes differentiation of the supplied materials; the relative cost of the input materials, as compared with the total product cost and the selling price; the cost involved in switching suppliers; the presence of substitute input materials; etc. In contrast, the bargaining power of the customers includes the purchase volume, buyer price sensitivity, presence of substitute or alternate products, etc. The threat of the new entrants is related to the capital cost of changing products, the barrier-to-entry, the brand equity, the switching cost, supply-chain access, etc. Finally, the threat of product substitutes includes buyer switching costs, the propensity to substitute, the relative price performance of substitutes, and the perceived product differentiation, which indicates the value of the product features beyond the competition offering.

The product-development team knows most of these forces, or is familiar with most of them, for routine product extensions. However, for new-to-the-world products, and even products intended for an adjacent market, it is critical to assess these forces.

1.8 Intellectual-Property Analysis

Intellectual-property, or patent, analysis is used to assess technical competitiveness, to forecast technological trends, and to plan for potential competition from disruptions and displacements by new technologies, all of which are important when developing a new product. As an example, the introduction of a new product to the market can make obsolete a new-product-development effort. For these reasons, an early awareness of the new technologies that may displace a product concept is crucial in realizing the return on the investment for a new product.

A patent for an invention is defined as the grant of a property right to the inventor that excludes others from practicing the invention. It is used to protect a product, giving the inventor an exclusivity to produce the product for a limited time, 17 years in the United States. Patentable inventions may include: (1) operating methods or processes, (2) physical structures such as the composition of matter, and (3) product features or articles. Recently, these have been expanded to include: (4) algorithms and (5) business processes.

Using the innovation map described in Section 1.3, the product-development team can identify key inventions in material, process/manufacturing, and product technology that enable

product differentiation in the marketplace. These inventions are often protected by patents or defensive publications, or are kept as trade secrets. When picket-fencing a product, alternate technologies or pathways to produce a similar product are often protected as well.

The primary strength of patent analysis is as a leading indicator of technological change, offering an efficient way of identifying technological discontinuity. Patent analysis usually begins with a patent search, followed by analysis of the patents located. Until recently, patent searches were carried out by experts using specialized tools and databases. Today, patent searches are easily achieved using the Google advanced patent search on the Internet.

A Google advanced patent search locates patents using user-supplied keywords, patent numbers, patent titles, inventor names, assignee names, patent classifications, issue dates, and filing dates. Normally, searches are first carried out using keywords. After appropriate keywords have been found, searches can be limited by other attributes such as the inventor, assignee (company name), and filing or issue dates. Because issue dates are often many years after filing dates, searches often use the filing date to obtain a historical perspective of competitive filings.

1.9 Feasibility Stage

The second stage of the Stage-GateTM Product-Development Process is the feasibility stage. The main objectives of this stage are to validate the superior concept(s) generated during the concept stage against the customer requirements, and to build the business case for the project. In addition, other issues are addressed including updating the market assessment, competitive analysis (including IP strategy), and examination of health-safety-environment concerns.

The key deliverables are: (1) an assessment of the extent to which the superior concepts fulfill the customer requirements, (2) a business case for capturing the potential economic value of the product in the face of competition, and (3) a base-case process flow diagram, when applicable, especially for the design of basic chemical products.

This stage involves the generation of product prototypes, their evaluation by the customers, customer feedback, and the redesign of superior concepts. In so doing, the business case is revised, as is the competitive analysis. The team prepares a complete business proposal, together with its recommendation. At this gate, the management team decides whether to further invest or abandon the project.

Validation of the feasibility of the superior concept(s) begins with the building of product prototypes. These prototypes are shared with selected potential customers in return for their feedback.

Depending upon the feedback, the team may modify the concept(s) by improving, adding, or removing features of the product. At this stage, preliminary manufacturing runs are conducted to verify the manufacturability of the product. Usually, manufacturing runs are done at a pilot-plant facility, with a few runs at a selected manufacturing site.

A business case development involves the preparation of a business proposal that covers the value proposition of the product, differentiating it from existing products; the targeted market; the size of opportunity; and the assessment of the business risk. The latter includes a detailed analysis of competitive offerings and a strategy to protect the business (IP strategy).

1.10 Development Stage

Having passed the feasibility gate, the team is authorized to proceed to the third stage of the SGDP, the development stage. The main objective of this stage is to fully develop the product, ensuring that it is manufacturable and delivers the promised value proposition to its customers. As necessary, detailed design, equipment-sizing, profitability analysis, and optimization are carried out. In addition, other issues are addressed including updating the market assessment, competitive analysis (including IP strategy), and examination of health-safety-environment concerns. The key deliverables are the product specifications, the manufacturing feasibility assessment, and the detailed process design—especially for the basic chemical products.

This stage involves the development of the product construction specifications. In this stage, the construction, features, and complete specifications are developed. Also, customers are contacted more frequently in an attempt to align their FTS and NUD requirements more closely with the final product specifications. The team prepares a complete manufacturing assessment focusing on the manufacturing feasibility evaluation of the new product. Of particular interest is the capital investment required to manufacture the product. Manufacturing assessment often involves several manufacturing runs at existing manufacturing sites to evaluate their suitability for producing the product. In this regard, the team normally prepares a risk analysis of using the existing equipment. When necessary, a capital investment estimate is prepared for a new or modified manufacturing facility. Potential manufacturing sites are also identified and their performance is evaluated. When the project involves a significant investment for a new or modified manufacturing facility, a revised business assessment is completed.



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Process creation, is implemented by a design team when designing a process to manufacture a basic chemical product. It describes the components of the preliminary database and suggests several sources, including the possibility of carrying out laboratory experiments. Then, using the database, it shows how to create a synthesis tree, with its many promising flow-sheets, for consideration by the design team. This is accomplished first for the design of a continuous process to produce a commodity chemical, vinyl chloride, and subsequently, for the design of a batch process to produce a pharmaceutical.

For each of the most promising alternatives in the synthesis tree, a base-case design is created. Because this is central to the work of all design teams, the strategy for creating a detailed process flow diagram is covered and the need for pilot-plant testing is discussed.

2.1 Preliminary Database Creation

Having completed an initial assessment of the need for a process design, and having conducted a literature search, the design team normally seeks to organize the data required for the design into a compact database, one that can be accessed with ease as the team proceeds to create process flowsheets and develop a base-case design. At this stage, several alternatives are being considered, involving several raw materials, the desired products, and several by products and reaction intermediates. For these chemicals, basic thermo-physical properties are needed, including molecular weight, normal boiling point, freezing point, critical properties, standard enthalpy and Gibbs free energy of formation, and vapor pressures, densities, heat capacities, and latent heats as a function of temperature. If chemical reactions are involved, some rudimentary information concerning the rates of the principal chemical reactions, such as conversion and product distribution as a function of space velocity, temperature, and pressure, is often needed before initiating the process synthesis steps. When necessary, additional data are located, or measured in the laboratory, especially when the design team gains enthusiasm for a specific processing concept. In addition, the team needs environmental and safety data, including information on the toxicity of the chemicals, how they affect animals and humans, and flammability in air. Material Safety Data Sheets (MSDSs) will be available for chemicals already being produced but will have to be developed for new chemicals. Also, for preliminary economic evaluation, chemical prices are needed. Additional information, such as transport properties, detailed chemical kinetics, the corrosivity of the chemicals, heuristic parameters, and data for sizing equipment, is normally not needed during process creation. It is added by the design team, after a

detailed process flow diagram has been created, and before work on the detailed design of the equipment commences.

When the data are assembled, graphs are often prepared with curves positioned to provide a good representation, especially for experimental data with scatter. Alternatively, the coefficients of equations, theoretical or empirical, are computed using regression analysis programs. This is especially common for thermophysical property data, such as the vapor pressure, P^S , as a function of the temperature, T , and vapor–liquid equilibrium data.

2.2 Thermophysical Property Data

For basic properties such as molecular weight, normal boiling point, melting point, and liquid density (often at 208C), the CRC Handbook of Chemistry and Physics (CRC Press, Boca Raton, FL, annual) provides a compilation for a large number of organic and inorganic compounds. In addition, it provides vapor pressure data and enthalpies and free energies of formation for many of these compounds, as well as selected properties, such as the critical temperature, for just a few of these compounds. Similar compilations are provided by Perry's Chemical Engineers' Handbook (Green and Perry, 2008), Properties of Gases and Liquids (Poling et al., 2001), and Data for Process Design and Engineering Practice (Woods, 1995). In addition, extensive databases for as many as 15,000 compounds are provided by process simulators (e.g., ASPEN PLUS, ASPEN HYSYS, UNISIM, CHEMCAD, PRO/II, BATCH PLUS, and SUPERPRO DESIGNER), as discussed in Section 3.4. These are extremely useful as they are accessed by large libraries of programs that carry out material and energy balances, and estimate equipment sizes and costs.

Because phase equilibria are important in most chemical processes, design teams usually spend considerable time assembling data, especially vapor–liquid and liquid–liquid equilibrium data. Over the years, thousands of articles have been published in which phase equilibria data are provided. These can be accessed by a literature search, although the need to search the literature has largely been negated by the extensive compilation provided in Vapor–Liquid Equilibrium Data Collection (Gmehling et al., 1980). In this DECHEMA data bank, which is available both in more than 20 volumes and electronically, the data from a large fraction of the articles can be found easily. In addition, each set of data has been regressed to determine interaction coefficients for the binary pairs to be used to estimate liquid-phase activity coefficients for the NRTL, UNIQUAC, Wilson, etc., equations. This database is also accessible

by process simulators. For example, with an appropriate license agreement, data for use in ASPEN PLUS can be retrieved from the DECHEMA database over the Internet. For non-ideal mixtures, the extensive compilation of Gmehling (1994) of azeotropic data is very useful.

2.3 Environmental and Safety Data

Design teams need toxicity data for raw materials, products, by products, and intermediates incorporated in a process design. In toxicology laboratories operated by chemical companies and governmental agencies, such as the U.S. Environmental Protection Agency (EPA) and the U.S. Food and Drug Administration (FDA), tests are run to check the effects of various chemicals on laboratory animals. The chemicals are administered in varying dosages, over differing periods, and in different concentrations, stimulating effects that are measured in many ways, including effects on the respiratory system, the skin, and the onset of cancer. In most cases, the results are provided in extensive reports or journal articles. In some cases, chemicals are difficult to classify as toxic or nontoxic.

Already it is well known that a number of common chemicals are toxic to humans and need to be avoided. One source of information on these chemicals is the Toxic Chemical Release Inventory (TRI), which is maintained by the U.S. EPA, and includes over 600 chemicals. A list of these chemicals is available at the Internet site:

<http://www.epa.gov/tri/chemical/index.htm>

Another source is provided by the ratings of the National Fire Protection Association (NFPA), which are tabulated for many chemicals in *Data for Process Design and Engineering Practice* (Woods, 1995). The first of three categories is titled “Hazard to Health” and entries are rated from 0 to 4, with 0 meaning harmless and 4 meaning extremely hazardous.

In addition, tables of flammability data are also available for aerosols and polymers in *Perry’s Chemical Engineers’ Handbook* (Green and Perry, 2008). The NFPA ratings provide a less quantitative source for many chemicals under “Flammability Hazard,” which is the second of the three categories (also rated from 0 to 4).

2.4 Chemical Prices

Economics data are often related to supply and demand, and consequently they fluctuate and are much more difficult to estimate. Most companies, however, carry out market studies and have a basis for projecting market size and chemical prices. In view of the uncertainties, to be safe,

economic analyses are often conducted using a range of chemical prices to determine the sensitivity of the results to specific prices. One widely used source of prices of commodity chemicals is from ICIS Chemical Business (formerly Chemical Market Reporter), a weekly publication. Their Web site, <http://www.icis.com/StaticPages/Students.htm>, provides information for students in their Knowledge Zone. It should be noted, however, that these prices may not reflect the market situation in a particular location; nevertheless, they provide a good starting point. In addition, commodity chemical prices may be found via ICIS pricing. Obviously, to obtain better estimates, at least for the immediate future, the manufacturers of the chemicals should be contacted directly. Lower prices than those listed can often be negotiated. Articles on chemicals of commerce in trade magazines can be searched for on the Web site <http://www.findarticles.com>. Subscribers to ICIS Chemical Business can also obtain more recent market trends and data derived from both their ICIS news and ICIS pricing services.

2.5 Experiments

Many design concepts are the result of extensive experiments in the laboratory, which provide valuable data for the design team. Often, however, laboratory experiments are carried out in small vessels, using small quantities of expensive solvents, and under conditions where the conversion and selectivity to the desired product are far from optimal. For this reason, as a design concept becomes more attractive, it is common for the design team to request additional experiments at other conditions of compositions, temperatures, and pressures, and using solvents that are more representative of those suitable for large-scale production. In cases where no previous in-house experimental work has been done, laboratory programs are often initiated at the request of the design team, especially when estimates of the rates of reaction are not very reliable. When chemical reactions involve the use of catalysts, it is essential that experiments be conducted on catalyst life using feedstocks that are representative of those to be used for large-scale production, and that may contain potential catalyst poisons.

Laboratory experiments may also be necessary to aid in the selection and preliminary design of separation operations. The separation of gas mixtures requires consideration of absorption, adsorption, and gas permeation, all of which may require the search for an adequate absorbent, adsorbent, and membrane material, respectively. When nonideal liquid mixtures are to be separated, laboratory distillation experiments should be conducted early because the possibility of azeotrope formation can greatly complicate the selection of adequate separation equipment, which may involve

the testing of one or more solvents or entrainers. When solids are involved, early laboratory tests of such operations as crystallization, filtration, and drying are essential.

2.6 Preliminary Process Synthesis

Design teams use many kinds of processing operations to carry out chemical reactions and to separate products and by products from each other and from unreacted raw materials. In many respects, one of the greatest challenges in process design involves the synthesis of configurations that produce chemicals in a reliable, safe, and economical manner, and at high yield with little or no waste. Until recently, this part of the design process, often referred to as process synthesis, in which many kinds of process operations are configured into flowsheets, was performed from experience gained in similar processing situations, with little formal methodology.

Thanks to research over the past 35 years, coupled with methods of decision-tree analysis and mathematical programming, synthesis strategies have become more quantitative and scientific. After examining two case studies involving the synthesis of a vinyl chloride process and of a process to manufacture tissue plasminogen activator (tPA), the reader should have a good appreciation of the principal issues in process synthesis.

Preliminary process synthesis occurs after an alternative processing concept has been created. Having defined the concept and assembled the preliminary database, usually with some experimentation, the design team sets out to synthesize a flowsheet of process operations to convert the raw materials to the desired products. First, it decides on the state of the raw materials, products, and by products, before assembling different configurations of the process operations.

To introduce this approach, this section begins by reviewing the concept of the chemical state, followed by a review of the principal operations, before covering several of the key steps in process synthesis, and utilizing them to create the vinyl chloride and tPA processes. Throughout this development, it should be clear that the synthesis or invention of a chemical process involves the generation and solution of a large combinatorial problem. Here, intuition and experience are as important to the design team as to the composer or artist.

2.7 Chemical State

As the first step in process synthesis, the design team must decide on raw material and product specifications. These are referred to as states. To define the state, values of the following conditions are needed:

1. Mass (flow rate)
2. Composition (mole or mass fraction of each chemical species of a unique molecular type)
3. Phase (solid, liquid, or gas)
4. Form, if solid phase (e.g., particle size distribution and particle shape)
5. Temperature
6. Pressure

In addition, some well-defined properties, such as the intrinsic viscosity, average molecular weight, color, and odor of a polymer, may be required. These are often defined in connection with the research and marketing departments, which work to satisfy the requests and requirements of their customers. It is not uncommon for a range of conditions and properties to be desired, some of which are needed intermittently by various customers as their downstream requirements vary. When this is the case, care must be taken to design a process that is sufficiently flexible to meet changing demands.

For most chemicals, the scale (i.e., production level or flow rate) of the process is a primary consideration early in the design process. Working together with the marketing people, the scale of the process is determined on the basis of the projected demand for the product. Often the demographics of the most promising customers have an important impact on the location of the plant and the choice of its raw materials. As the scale and the location are established, the composition, phase, form, temperature, and pressure of each product and raw-material stream are considered as well. When the desired states of these streams have been identified, the problem of process synthesis becomes better defined.

It is noteworthy that once the state of a substance is fixed by conditions 1–6, all physical properties (except for the form of a solid), including viscosity, thermal conductivity, color, refractive index, and density, take on definite values. Furthermore, the state of a substance is independent of its position in a gravitational field and its velocity. Although there are other conditions (magnetic field strength, surface area) whose values are needed under certain conditions, the six conditions listed above are usually sufficient to fix the state of a substance.

2.8 Process Operations

Throughout the chemical engineering literature, many kinds of equipment, so-called unit operations, are described, including distillation columns, absorbers, strippers, evaporators, decanters, heat exchangers, filters, and centrifuges, just to mention a few.

1. Chemical reaction
2. Separation of chemical mixtures

3. Phase separation
4. Change of temperature
5. Change of pressure
6. Change of phase
7. Mixing and splitting of streams or batches
8. Operations on solids, such as size reduction and enlargement

Since these are the building blocks of nearly all chemical processes, it is common to create flowsheets involving these basic operations as a first step in process synthesis. Then, in a task integration step, operations are combined where feasible. Chemical reaction operations are at the heart of many chemical processes. They are inserted into a flowsheet to effect differences in the molecular types between raw-material and product streams. To this end, they involve the chemistry of electron transfers, free-radical exchanges, and other reaction mechanisms, to convert the molecular types of the raw materials into products of other molecular types that have the properties sought by a company's customers. Clearly, the positioning of the reaction operations in the flowsheet involves many considerations, including the degree of conversion, reaction rates, competing side reactions, and the existence of reactions in the reverse direction (which can result in constraints on the conversion at equilibrium). These, in turn, are related closely to the temperature and pressure at which the reactions are carried out, the methods for removing or supplying energy, and the catalysts that provide competitive reaction rates and selectivity to the desired products.

Separation operations appear in almost every process flowsheet. They are needed whenever there is a difference between the desired composition of a product or an inter-mediate stream and the composition of its source, which is either a feed or an intermediate stream. Separation operations are inserted when the raw materials contain impurities that need to be removed before further processing, such as in reactors, and when products, by products, and unreacted raw materials coexist in a reactor effluent stream. The choice of separation operations depends first on the phase of the mixture and second on the differences in the physical properties of the chemical species involved. For liquid mixtures, when differences in volatilities (i.e., vapor pressure) are large, it is common to use vapor-liquid separation operations (e.g., distillation), which are by far the most common. For some liquid mixtures, the melting points differ significantly and solid-liquid separations, involving crystallization, gain favor. When differences in volatilities and melting points are small, it may be possible to find a solvent that is selective for some components and not others, and to use a liquid-liquid separation operation. For other mixtures, particularly gases, differences in absorbability (in an absorbent),

adsorbability (on an adsorbent; e.g., activated carbon, molecular sieves, or zeolites), or permeability through a membrane may be exploited with adsorption and membrane separation operations. Many separation operations require phase-separation operations, which may be accomplished by vessels called flash drums for vapor–liquid separation, by decanters for liquid–liquid separation, and by filters and centrifuges for liquid–solid separation.

The need to change temperatures usually occurs throughout a chemical process. In other words, there are often differences in the temperatures of the streams that enter or leave the process or that enter or leave adjacent process operations, such as reaction and separation operations. Often a process stream needs to be heated or cooled from its source temperature to its target temperature. This is best accomplished through heat exchange with other process streams that have complementary cooling and heating demands. In the examples of process synthesis, heating and cooling operations are inserted into the flowsheet to satisfy the heating and cooling demands, and a few of the concepts associated with heat integration.

The positioning of pressure-change operations such as gas compressors, gas turbines or expanders, liquid pumps, and pressure-reduction valves in a process flowsheet is often ignored in the early stages of process design. As will be seen, it is common to select the pressure levels for reaction and separation operations. When this is done, pressure-change operations will be needed to decrease or increase the pressure of the feed to the particular operation. In fact, for processes that have high power demands, usually for gas compression, there is often an opportunity to obtain much of the power through integration with a source of power, such as turbines or expanders, which are pressure-reduction devices. In process synthesis, however, where alternative process operations are being assembled into flowsheets, it has been common to disregard the pressure drops in pipelines when they are small relative to the pressure level of the process equipment. Liquid pumps to overcome pressure drops in lines and across control valves and to elevate liquid streams to reactor and column entries often have negligible costs. Increasingly, as designers recognize the advantages of considering the controllability of a potential process while developing the base-case design, the estimation of pressure drops gains importance because flow rates are controlled by adjusting the pressure drop across a valve. Often there are significant differences in the phases that exit from one process operation and enter another. For example, hot effluent gases from a reactor are condensed, or partially condensed, often before entering a separation operation, such as a vapor–liquid separator (e.g., a flash vessel or a distillation tower). In process synthesis, it is common to position a phase-change operation using temperature- and/or pressure-reduction operations, such as heat exchangers and valves.

The mixing operation is often necessary to combine two or more streams and is inserted when chemicals are recycled and when it is necessary to blend two or more streams to achieve a product specification. In process synthesis, mixing operations are inserted usually during the distribution of chemicals, a key step that is introductory. Because the impact of mixing on the thermodynamic efficiency and the utilization of energy is often very negative it is usually recommended that mixer operations not be introduced unless they are necessary—for example, to avoid discarding unreacted chemicals. In this regard, it is noteworthy that mixing is the reverse of separation. Although there is an energy requirement in separating a stream into its pure constituents, mixing can be accomplished with no expenditure of energy other than the small amount of energy required when an agitator is used to speed up the mixing process. In cases where the streams are miscible and of low viscosity, mixing is accomplished easily by joining two pipes, avoiding the need for a mixing vessel. Splitting a stream into two or more streams of the same temperature, pressure, and composition is also readily accomplished in the piping.

2.9 Synthesis Steps

Given the states of the raw-material and product streams, process synthesis involves the selection of processing operations to convert the raw materials to products. In other words, each operation can be viewed as having a role in eliminating one or more of the property differences between the raw materials and the desired products. As each operation is inserted into a flowsheet, the effluent streams from the new operation are closer to those of the required products. For example, when a reaction operation is inserted, the stream leaving often has the desired molecular types, but not the required composition, temperature, pressure, and phase. To eliminate the remaining differences, additional operations are needed. As separation operations are inserted, followed by operations to change the temperature, pressure, and phase, fewer differences remain. In one parlance, the operations are inserted with the goal of reducing the differences until the streams leaving the last operation are identical in state to the required products. Formal, logic-based strategies, involving the proof of theorems that assert that all of the differences have been eliminated, have been referred to as means–end analysis. In process synthesis, these formal strategies have not been developed beyond the synthesis of simple processes. Several general observations, however, are noteworthy before proceeding with the examples. First, like the vinyl chloride and tPA processes to be discussed next, most chemical processes are built about chemical reaction and/or separation operations. Consequently, the steps involved in synthesizing these processes are remarkably similar to those for the manufacture of other chemicals. As the syntheses proceed, note that many alternatives should be considered in the application of each step, many

of which cannot be eliminated before proceeding to the next steps. The result is that, at each step, a new set of candidate flowsheets is born. These are organized into synthesis trees as the steps are applied to create the vinyl chloride and tPA processes. The synthesis trees are compact representations of the huge combinatorial problem that almost always develops during process synthesis. As will be seen, approaches are needed to eliminate the least promising branches as soon as possible, to simplify the selection of a near-optimal process flowsheet.

2.10 Continuous or Batch Processing

When selecting processing equipment in the task integration step, the production scale strongly impacts the operating mode. For the production of commodity chemicals, large-scale continuous processing units are selected, whereas for the production of many specialty chemicals as well as industrial and configured consumer chemical products, small-scale batch processing units are preferable. The choice between continuous or batch, or possibly semi-continuous, operation is a key decision. Over the years, large commercial plants have been built, some of which produce over 1 billion lb/yr. Hence, polyvinyl chloride, and the monomer from which it is derived, is referred to commonly as a commodity chemical that is produced continuously, rather than in batch, virtually everywhere. Historically, vinyl chloride was discovered in 1835 in the laboratory of the French chemist Regnault, and the first practical method for polymerizing vinyl chloride was developed in 1917 by the German chemists Klatte and Rollett (Leonard, 1971). Vinyl chloride is an extremely toxic substance and, therefore, industrial plants that manufacture it or process it must be designed carefully to satisfy government health and safety regulations.

Synthesis Tree

Throughout the synthesis of the vinyl-chloride process, branches have been added to the synthesis tree to represent the alternative flowsheets being considered. The bold branches trace the development of just one flow-sheet as it evolves. Clearly, there are many alternative flowsheets, and the challenge in process synthesis is to find ways to eliminate whole sections of the tree without doing much analysis. By eliminating reaction paths 1 and 2, as much as 40% of the tree is eliminated in the first synthesis step. Similar screening techniques are applied by the design team in every step. To satisfy the objective of generating the most promising flowsheets, care must be taken to include sufficient analysis in each synthesis step to check that each step does not lead to a less profitable flowsheet or exclude the most profitable flowsheet prematurely.

2.11 Heuristics

It is important to keep in mind that, when carrying out the steps in preliminary process synthesis, the resulting synthesis tree is closely related to any heuristics or rules of thumb used by the design team. In the vinyl-chloride example, emphasis was placed on the synthesis steps, and not on the use of heuristics by the design team. An exception is the heuristic that it is cheaper to pump a liquid than compress a gas.

2.12 Development Of The Base-Case Design

At some point in the synthesis of alternative flowsheets, it becomes important to select one or two of the most promising alternatives for further development into the so-called base-case design(s). To accomplish this, the design team is usually expanded, mostly with chemical engineers, or assisted by more specialized engineers, as the engineering workload is increased significantly. With expanded engineering involvement, the design team sets out to create a detailed process flow diagram and to improve the task integration begun in preliminary process synthesis. Then, in preparation for the detailed design work to follow, a detailed database is created, a pilot plant is often constructed to test the reaction steps and the more important, less understood separation operations, and a simulation model is commonly prepared. As the design team learns more about the process, improvements are made, especially changes in the flow diagram to eliminate processing problems that had not been envisioned. In so doing, several of the alternative flow sheets generated in preliminary process synthesis gain more careful consideration, as well as the alternatives generated by the algorithmic methods, in detailed process synthesis [which often continues as the base-case design(s) is being developed].

2.13 Flow diagrams

As the engineering work on the base-case design proceeds, a sequence of flow diagrams is used to provide a crucial vehicle for sharing information. The three main types are introduced in this subsection, beginning with the simplest block flow diagram (BFD), proceeding to the process flow diagram (PFD), and concluding with the piping and instrumentation diagram (P&ID).

2.14 Block Flow Diagram (BFD)

The block flow diagram represents the main processing sections in terms of functional blocks. Note that the diagram also indicates the overall material balances and the conditions at each stage, where appropriate. This level of detail is helpful to summarize the principal processing sections and is appropriate in the early design stages, where alternative processes are usually under consideration.

2.15 Process Flow Diagram (PFD)

Process flow diagrams provide a more detailed view of the process. These diagrams display all of the major processing units in the process (including heat exchangers, pumps, and compressors), provide stream information, and include the main control loops that enable the process to be regulated under normal operating conditions. Often, preliminary PFDs are constructed using the process simulators. Subsequently, more detailed PFDs are prepared using software such as AUTOCAD and VISIO.

2.16 Processing Units

Icons that represent the units are linked by arcs (lines) that represent the process streams. The drawing conventions for the unit icons are taken from accepted standards, for example, the ASME (American Society for Mechanical Engineers) standards (ASME, 1961). Note that each unit is labelled according to the convention U-XYX, where U is a single letter identifying the unit type (V for vessel, E for exchanger, R for reactor, T for tower, P for pump, C for compressor, etc.). X is a single digit identifying the process area where the unit is installed, and YY is a two-digit number identifying the unit itself. Thus, for example, E-100 is the identification code for the heat exchanger that condenses the overhead vapors from the chlorination reactor. Its identification code indicates that it is the 00 item installed in plant area 1.

2.17 Process Integration

With the detailed process flow diagram completed, the task-integration step, which was initiated in the preliminary process synthesis, is revisited by the design team. The assumptions are checked and opportunities are sought to improve the designs of the processing units, and to achieve a more efficient process integration. In the latter, attempts are made to match cold streams that need to be heated with hot streams that have cooling requirements, so as to reduce the need for external

utilities such as steam and cooling water. In addition, where possible, power is extracted from hot streams at elevated pressures, so as to drive compressors and pumps. Also, when solvents, such as water, are used as mass separating agents, opportunities are sought to reduce the amount of solvent used through mass integration. Often, significant improvements can be made in the process design beyond those achievable in the preliminary process synthesis.

2.18 Detailed Database

Having completed the process flow diagram (PFD), the design team seeks to check its key assumptions further and to obtain the additional information needed to begin work on the detailed design. This usually involves three activities in parallel, the first of which is to create a detailed database by refining and adding to the preliminary database. In the other two activities, a pilot plant is constructed to confirm that the equipment items operate properly and to provide data for the detailed data bank, and a simulation model is prepared to enable the team to project the impact of changes in the design and operation parameters, such as temperatures, pressures, reflux ratios, and the number of stages.

In creation of the detailed database, it is common to add transport and kinetics data, as well as data concerning the feasibility of the separations, the identity of any forbidden matches in heat exchange, heuristic parameters, and data for sizing the equipment. Each process requires somewhat different data, and hence it is inappropriate to generalize. However, it is instructive to examine the mix of data needed by a design team in connection with the vinyl-chloride.

Process Simulation

The process simulator usually plays an important role, even if a simulation model is not prepared for the entire flowsheet. When parts of a simulation model exist, it is common for the design team to assemble a more comprehensive model, one that enables the team to examine the effect of parametric changes on the entire process. In other cases, when the process simulators have not been used for design, a simulation model is often created for comparison with the pilot-plant data and for parametric studies.

High-speed PCs and laptop computers, which have excellent graphical user interfaces (GUIs), have replaced work-stations as the preferred vehicle for commercial simulators, and are now finding widespread use throughout the chemical process industries.

2.19 Pilot-Plant Testing

Clearly, as the detailed database is assembled, the needs for pilot-plant testing become quite evident. For the manufacture of new chemicals, a pilot plant can produce quantities of product suitable for testing and evaluation by potential customers. Very few processes that include reaction steps are constructed without some form of pilot-plant testing prior to doing detailed design calculations. This is an expensive, time consuming step that needs to be anticipated and planned for by the design team as early as possible, so as to avoid extensive delays. Again, although it is inappropriate to generalize, the vinyl-chloride process provides good examples of the need for pilot-plant testing and the generation of data for detailed design calculations.

Kinetic data are needed for both the chlorination and pyrolysis reactors, as well as to determine the rate of carbon deposition. In all three cases, it is unlikely that adequate data can be located in the open literature. Consequently, unless sufficient data exist in company files, or were taken in the laboratory and are judged to be adequate, pilot-plant testing is needed. Generally, the pilot-plant tests are conducted by a development team working closely with the design team. As the data are recorded, regression analyses are commonly used to compute the coefficients of compact equations to be stored in the database.

As mentioned in connection with the need for laboratory experiments, pilot-plant tests also help to identify potential problems that arise from small quantities of impurities in the feed streams, and when unanticipated by products are produced, usually in small quantities, that have adverse effects such as to impart an undesired color or smell to the product. When a catalyst is used, the impact of these species needs to be studied, and, in general, the useful life of the catalyst needs to be characterized. Pilot plants can also verify separation schemes developed during process design

Computing packages that model the process units are introduced and utilized to model the highly integrated flow-sheets commonly designed to achieve more profitable operation. As has been mentioned, these packages are referred to as process simulators, most of which are used to simulate potential processes in the steady state—that is, to determine the unknown temperatures, pressures, and component and total flow rates at steady state. More recently, these packages have been extended to permit the dynamic simulation of processes and their control systems as they respond to disturbances and changes in operating points.

For the production of commodity chemicals, as the alternative flowsheets evolve, it is common to perform these calculations assuming operation in the steady state; hence, many steady-state simulators have become available to process engineers. For the production of specialty chemicals in batch processes, it is common to perform similar calculations using batch process simulators.

The multimedia modules, which can be downloaded from the Wiley Website associated with this book also explain how to use the dynamic simulators. Emphasis is placed on HYSYS. Using HYSYS, the design team can complete a steady-state simulation, add controllers, and activate the integrator to carry out a dynamic simulation. Similar facilities are provided in ASPEN DYNAMICS by Aspen Technology, Inc. In addition, the multimedia modules provide video segments from a large-scale petrochemical complex to illustrate some of the equipment being modelled, tutorials on the estimation and regression of physical property data. Also, .bkp and .hsc files for the ASPEN PLUS and HYSYS.

2.20 Degrees of Freedom

A degrees-of-freedom analysis (Smith, 1963; Rudd and Watson, 1968; Myers and Seider, 1976) is incorporated in the development of each subroutine (or block, or model) that simulates a process unit. These subroutines solve sets of $N_{\text{Equations}}$ involving $N_{\text{Variables}}$, where $N_{\text{Equations}} < N_{\text{Variables}}$. Thus, there are $N_{\text{Variables}} - N_{\text{Equations}}$ degrees of freedom, or input (decision) variables. Most subroutines are written for known values of the input stream variables, although HYSYS permits specification of a blend of input and output stream variables, or output stream variables entirely.

2.21 Process and Simulation Flowsheets

As in the steady-state simulation of continuous processes, it is convenient to convert from a process flowsheet to a simulation flowsheet. To accomplish this, it is helpful to be familiar with the library of models (or procedures) and operations provided by the simulator. For example, using SUPER PRO DESIGNER to simulate two fermentation reactors in series, quickens the process. In BATCH PLUS, however, this conversion is accomplished without drawing the simulation flowsheet, since the latter is generated automatically on the basis of the recipe specifications for each equipment item.

In the simulation flowsheets, the arcs represent the streams that convey the batches from equipment item to equipment item. Each arc bears the stream name and represents the transfer of information associated with each stream; that is, the mass of each species per batch, temperature, pressure, density, and other physical properties.

The icons represent the models for each of the equipment items. Unlike for the simulation of continuous processes, these models involve a sequence of process operations, which are specified by the designer. Typically, these operations are defined as a recipe or campaign for each equipment item, and usually involve charging the chemicals into the vessel, processing the chemicals, removing the chemicals from the vessel, and cleaning the vessel.



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UNIT – III – Process Engineering – SCHA1702

Normally, design teams use heuristics when generating the alternatives that make up a synthesis tree. For the most part, heuristics are easy to apply; that is, they involve the setting of temperatures, pressures, excess amounts of chemicals, and so on. Often, they require little analysis in that simple material balances can be completed without iterations before proceeding to the next synthesis step. Consequently, several promising flowsheets are generated rapidly, with relatively little effort. The emphasis of the design team shifts to the creation of a base-case design. The assumptions are checked, a process flow diagram is assembled and a complete material and energy balance is carried out, often using the process simulators. Clearly, the heuristics used by a design team to generate the synthesis tree are crucial in the design process. A total of 53 heuristics are being used in process industries.

3.1 Raw Materials And Chemical Reactions

Heuristic 1: Select raw materials and chemical reactions to avoid, or reduce, the handling and storage of hazardous and toxic chemicals.

The selection of raw materials and chemical reactions is often suggested by chemists, biologists, biochemists, or other persons knowledgeable about the chemical conversions involved. In recent years, with the tremendous increase in awareness of the need to avoid handling hazardous and toxic chemicals, in connection with environmental and safety regulations raw materials and chemical reactions are often selected to protect the environment and avoid the safety problems that are evident in Material Safety Data Sheets (MSDSs). For example, recall that when the vinyl-chloride process was synthesized, the reaction of acetylene with HCl was rejected because of the high cost of acetylene. Today, in addition, this reaction path would be rejected on the basis of the high reactivity of acetylene and the difficulty of ensuring safe operation in the face of unanticipated disturbances.

In connection with the handling of hazardous chemicals, the 1984 accident in Bhopal, India, in which water was accidentally mixed with the active intermediate methyl isocyanate, focused worldwide attention on the need to reduce the handling of highly reactive intermediates. Within an hour of the accident, a huge vapor cloud swept across Bhopal, leading to the death of over 3,800 victims in the vicinity of the Union Carbide plant. This accident, together with the discovery of polluted groundwaters adjacent to chemical plants, especially those that process nuclear fuels, have led safety and environment experts to call for a sharp reduction in the handling of hazardous chemicals.

3.2 Distribution Of Chemicals

Heuristic 2: Use an excess of one chemical reactant in a reaction operation to consume completely a valuable, toxic, or hazardous chemical reactant. The MSDSs will indicate which chemicals are toxic and hazardous. After the reaction operations are positioned in a process flowsheet, the sources of chemicals (i.e., the feed streams and reactor effluents) are distributed among the sinks for chemicals (i.e., the feed streams to the reaction operations and the products from the process). In this distribution, decisions are made concerning (1) the use of one chemical reactant in excess in a reaction operation, (2) the handling of inert species that enter in the feed streams, and (3) the handling of undesired by products generated in side reactions. One distribution of chemicals for the vinyl-chloride process involves stoichiometric amounts of ethylene and chlorine fed to the direct-chlorination reactor. Alternatively, an excess of ethylene can be utilized. In this distribution, the reactor is designed to consume completely the hazardous and toxic chlorine, but the recovery of unreacted ethylene from the dichloroethane product is required. Clearly, an important consideration is the degree of the excess, that is, the ethylene/chlorine ratio. It governs the costs of separation and recirculation, and often plays a key role in the process economics. In many design strategies, this ratio is set using heuristics, with larger ratios used to ensure consumption of the most hazardous chemicals. Eventually, as a base-case design evolves, the ratio is varied systematically, often using a process simulator. In mathematical programming strategies, it is treated as a design variable, to be varied during optimization, with a lower bound. Note that for exothermic reactions, the excess chemical often serves the useful function of absorbing the heat of reaction and thereby maintaining more moderate temperatures. This is an important approach to handling large heats of reaction and is considered with several common alternatives on heat removal from exothermic reactors. An excess of one chemical reactant is also used to increase conversion of the other (limiting) reactant when the extent of reaction is limited by equilibrium. Also, side reactions can be minimized by using an excess of one reactant.

3.3 Inert Species

Heuristic 3: When nearly pure products are required, eliminate inert species before the reaction operations when the separations are easily accomplished and when the catalyst is adversely affected by the inert, but not when a large exothermic heat of reaction must be removed.

Often impure feed streams contain significant concentrations of species that are inert in chemical reaction operations. When nearly pure products are required, an important decision concerns whether impurities should be removed before or after reaction operations. Consider in which two reaction operations have been positioned. An impure feed stream of reactant C contains the inert species D, and hence a decision is required concerning whether to remove D before or after reaction step 2. Clearly, the ease and cost of the separations, that is, D from C, and D from E (plus unreacted A and C), must be assessed. This can be accomplished by examining the physical properties on which the separations are based upon.

3.4 Purge Streams

Heuristic 4: Introduce purge streams to provide exits for species that enter the process as impurities in the feed or are formed in irreversible side reactions, when these species are in trace quantities and/or are difficult to separate from the other chemicals. Lighter species leave in vapor purge streams, and heavier species exit in liquid purge streams.

Trace species, often introduced as impurities in feed streams or formed in side reactions, present special problems when the chemicals are distributed in a flowsheet. In a continuous process, these accumulate continuously unless a means is provided for their removal, either by reaction, separation, or through purge streams. Since the reaction or separation of species in low concentration is usually costly, purge streams are used when the species are nontoxic and have little impact on the environment. Purge streams are also used for removing species present in larger amounts when their separation from the other chemicals in the mixture is difficult.

Heuristic 5: Do not purge valuable species or species that are toxic and hazardous, even in small concentrations (MSDSs). Add separators to recover valuable species. Add reactors to eliminate, if possible, toxic and hazardous species.

In some situations, the recovery of trace species from waste streams is an important alternative to purging. This, of course, is the case when an aqueous stream contains trace quantities of rare metals, as can occur when catalysts are impregnated on ceramic supports. In other situations—for example, in the handling of aqueous wastes—environmental regulations are such that trace

quantities of organic and inorganic chemicals must be recovered or converted into an environmentally acceptable form. One process to treat aqueous streams in the vicinity of leaking tanks is super-critical oxidation, using acoustic waves or lasers to produce plasmas. In this process, the waste species [including chlorinated hydrocarbons, pesticides, phenols (e.g., p-nitrophenol), and esters] are oxidized at temperatures and pressures associated with supercritical water (Hua et al., 1995a, b). Yet another example involves the catalytic conversion of hydro-carbons and carbon monoxide in the exhaust gases from internal combustion engines. Rather than purge the exhaust gases from a combustion engine, catalytic converters commonly convert carbon mon-oxide and nitrogen oxides to carbon dioxide and nitrogen, respectively. Again, the decision to insert a reaction step, rather than to separate or purge, in the early stages of process design is made often based on the availability of a catalyst and experience; that is, heuristics.

3.5 Recycle to extinction

Heuristic 6: By products that are produced in a reversible reaction in small quantities are usually not recovered in separators or purged. Instead they are usually recycled to extinction.

Often small quantities of chemicals are produced in side reactions, such as the reaction of benzene to form biphenyl in the toluene hydrodealkylation process. When the reaction proceeds irreversibly, small quantities of by products must be separated away, or purged; otherwise they will build up in the process until the process must be shut down.

When the reaction proceeds reversibly, however, it becomes possible to achieve an equilibrium conversion at steady state by recycling product species without removing them from the process. In so doing, it is often said that undesired by products are recycled to extinction. It is important to recognize this when distributing chemicals in a potential flowsheet so as to avoid the loss of chemicals through purge streams or the insertion of expensive separation operations. Recycle to extinction, which is considered is most effective when the equilibrium conversion of the side reaction is limited by a small chemical equilibrium constant at the temperature and pressure conditions in the reactor.

3.6 Selectivity

Heuristic 7: For competing reactions, both in series and parallel, adjust the temperature, pressure, and catalyst to obtain high yields of the desired products. In the initial distribution of chemicals, assume that these conditions can be satisfied. Before developing a base-case design, obtain kinetics data and check this assumption.

When chemical reactions compete in the formation of a desired chemical, the reaction conditions must be set carefully to obtain a desirable distribution of chemicals. Consider, for example, the series, parallel, and series-parallel reactions where species B is the desired product. For these and similar reaction systems, it is important to consider the temperature, pressure, ratio of the feed chemicals, and the residence time when distributing the chemicals. One example of series-parallel reactions occurs in the manufacture of allyl chloride.

3.7 Reactive Separations

Heuristic 8: For reversible reactions especially, consider conducting them in a separation device capable of removing the products, and hence driving the reactions to the right. Such reaction-separation operations lead to very different distributions of chemicals.

The last step in process synthesis is task integration, that is, the combination of operations into process units. In the synthesis steps recommended, reaction operations are positioned first, chemicals are distributed and separation operations are positioned, followed by temperature-, pressure-, and phase-change operations, before task integration occurs. In some cases, however, this strategy does not lead to effective combinations of reaction and separation operations, for example, reactive distillation towers, reactive absorption towers, and reactive membranes. Alternatively, when the advantages of merging these two operations are examined by a design team, a combined reaction-separation operation is placed in the flowsheet before chemicals are distributed, with a significant improvement in the economics of the design.

3.8 Separations

Separations Involving Liquid and Vapor Mixtures

Heuristic 9: Separate liquid mixtures using distillation, strip-ping, enhanced (extractive, azeotropic, reactive) distillation, liquid–liquid extraction, crystallization, and/or adsorption.

Heuristic 10: Attempt to condense or partially condense vapor mixtures with cooling water or a refrigerant. Then, use Heuristic 9.

Heuristic 11: Separate vapor mixtures using partial condensation, cryogenic distillation, absorption, adsorption, membrane separation, and/or de sublimation.

The selection of separation processes is dependent on the phase of the stream to be separated and the relative physical properties of its chemical species. Liquid and vapor streams are separated often using the strategy recommended by Douglas (1988) in *Conceptual Design of Chemical Processes*. This strategy is reproduced here using the original figures, slightly modified, with the publisher's permission. Note that the choice of type of separator is often influenced by the scale of the process, with distillation often favoured by economies-of-scale at large throughputs, and adsorption and membrane separation gaining favour as throughputs decrease.

When the reaction products are in the liquid phase, Douglas recommends that a liquid-separation system be inserted in the flowsheet. The liquid-separation system involves one or more of the following separators: distillation and enhanced distillation, stripping, liquid–liquid extraction, and so on, with the unreacted chemicals recovered in a liquid phase and recycled to the reaction operation.

Heuristic 12: Crystallize inorganic chemicals from a concentrated aqueous solution by chilling when solubility decreases significantly with decreasing temperature. Keep the solution at most 1 to 28F below the saturation temperature at the prevailing concentration. Use crystallization by evaporation, rather than chilling, when solubility does not change significantly with temperature.

Heuristic 13: Crystal growth rates are approximately the same in all directions, but crystals are never spheres. Crystal growth rates and sizes are controlled by limiting the extent of supersaturation, $S \propto C/C_{\text{saturation}}$, where C is concentration, usually in the range $1.02 < S < 1.05$. Growth rates are influenced greatly by the presence of impurities and of certain specific additives that vary from case to case.

Heuristic 14: Separate organic chemicals by melt crystallization with cooling, using suspension crystallization, followed by removal of crystals by settling, filtration, or centrifugation. Alternatively, use layer crystallization on a cooled surface, with scraping or melting to remove the crystals. If the melt forms a solid solution, instead of a eutectic, use repeated melting and freezing steps, called fractional melt crystallization, or zone melting to obtain nearly pure crystalline products.

Prior to crystallization, it is common to employ evaporation to concentrate a solution, particularly an aqueous solution of inorganic chemicals. Because of the relatively high cost of evaporating water, with its very large heat of vaporization, the following heuristics are useful for minimizing the cost.

Heuristic 15: Using multiple evaporators (called effects) in series, the latent heat of evaporation of water is recovered and reused. With a single evaporator, the ratio of the amount of water evaporated to the amount of external steam supplied to cause the evaporation is typically 0.8. For two effects, the ratio becomes 1.6; for three effects 2.4, and so forth. The magnitude of the boiling-point elevation caused by the dissolved inorganic compounds is a controlling factor in selecting the optimal number of effects. The elevation is often in the range of 3 to 108°F between solution and pure water boiling points. When the boiling-point rise is small, minimum evaporation cost is obtained with 8 to 10 effects. When the boiling-point rise is appreciable, the optimal number of effects is small, 6 or less. If necessary, boost interstage steam pressures with steam-jet or mechanical compressors.

Heuristic 16: When employing multiple effects, the liquid and vapor flows may be in the same or different directions. Use forward feed, where both liquid and vapor flow in the same direction, for a small number of effects, particularly when the liquid

feed is hot. Use backward feed, where liquid flows in a direction opposite to vapor flows, for cold feeds and/or a large number of effects. With forward feed, intermediate liquid pumps are not necessary, whereas they are for backward feed.

Heuristic 17: When crystals are fragile, effective washing is required, and clear mother liquor is desired, use: gravity, top-feed horizontal pan filtration for slurries that filter at a rapid rate; vacuum rotary-drum filtration for slurries that filter at a moderate rate; and pressure filtration for slurries that filter at a slow rate.

Heuristic 18: When cakes of low moisture content are required, use: solid-bowl centrifugation if solids are permitted in the mother liquor; centrifugal filtration if effective washing is required.

Heuristic 19: For granular material, free flowing or not, of particle sizes from 3 to 15 mm, use continuous tray and belt dryers with direct heat. For free-flowing granular solids that are not heat sensitive, use an inclined rotary cylindrical dryer, where the heat may be supplied directly from a hot gas or indirectly from tubes, carrying steam, that run the length of the dryer and are located in one or two rings concentric to and located just inside the dryer rotating shell. For small, free-flowing particles of 1 to 3 mm in diameter, when rapid drying is possible, use a pneumatic conveying dryer with direct heat. For very small free-flowing particles of less than 1 mm in diameter, use a fluidized-bed dryer with direct heat.

Heuristic 20: For pastes and slurries of fine solids, use a drum dryer with indirect heat. For a liquid or pumpable slurry, use a spray dryer with direct heat.

Heuristic 21: To remove a highly exothermic heat of reaction, consider the use of excess reactant, an inert diluent, or cold shots. These affect the distribution of chemicals and should be inserted early in process synthesis.

Heuristic 22: For less exothermic heats of reaction, circulate reactor fluid to an external cooler, or use a jacketed vessel or cooling coils. Also, consider the use of intercoolers between adiabatic reaction stages.

Heuristic 23: To control temperature for a highly endothermic heat of reaction, consider the use of excess reactant, an inert diluent, or hot shots. These affect the distribution of chemicals and should be inserted early in process synthesis.

Heuristic 24: For less endothermic heats of reaction, circulate reactor fluid to an external heater, or use a jacketed vessel or heating coils. Also, consider the use of inter heaters between adiabatic reaction stages.

Heuristic 25: Unless required as part of the design of the separator or reactor, provide necessary heat exchange for heating or cooling process fluid streams, with or without utilities, in an external shell-and-tube heat exchanger using counter current flow. However, if a process stream requires heating above 750°F, use a furnace unless the process fluid is subject to chemical decomposition.

Preliminary estimates of exit temperatures of streams flowing through a heat exchanger can be made with the following heuristics.

Heuristic 26: Near-optimal minimum temperature approaches in heat exchangers depend on the temperature level as follows:

108°F or less for temperatures below ambient.

208°F for temperatures at or above ambient up to 300°F.

508°F for high temperatures.

250 to 350°F in a furnace for flue gas temperature above inlet process fluid temperature.

Heuristic 27: When using cooling water to cool or condense a process stream, assume a water inlet temperature of 90°F (from a cooling tower) and a maximum water outlet temperature of 120°F.

Heuristic 28: Boil a pure liquid or close-boiling liquid mixture in a separate heat exchanger, using a maximum overall temperature driving force of 45°F to ensure nucleate boiling and avoid undesirable film boiling

Heuristic 29: When cooling and condensing a stream in a heat exchanger, a zone analysis, described, should be made to make sure that the temperature difference between the hot stream and the cold stream is equal to or greater than the minimum approach temperature at all locations in the heat exchanger. The zone analysis is performed by dividing the heat exchanger into a number of segments and applying an energy balance to each segment to determine corresponding stream inlet and outlet temperatures for the segment, taking into account any phase change. A process simulation program conveniently accomplishes the zone analysis.

Heuristic 30: Typically, a hydrocarbon gives an adiabatic flame temperature of approximately 3,500°F when using the stoichiometric amount of air. However, use excess air to achieve complete combustion and give a maximum flue gas temperature of 2,000°F. Set the stack gas temperature at 650 to 950°F to prevent condensation of corrosive components of the flue gas.

Heuristic 31: Estimate heat-exchanger pressure drops as follows:

1.5 psi for boiling and condensing.

3 psi for a gas.

5 psi for a low-viscosity liquid. 7–9 psi for a high-viscosity liquid.

20 psi for a process fluid passing through a furnace.

Heuristic 32: Quench a very hot process stream to at least 1,150°F before sending it to a heat exchanger for additional cooling and/or condensation. The quench fluid is best obtained from a downstream separator for the toluene hydro-dealkylation process. Alternatively, if the process stream contains water vapor, liquid water may be an effective quench fluid.

Heuristic 33: If possible, heat or cool a stream of solid particles by direct contact with a hot gas or cold gas, respectively, using a rotary kiln, a fluidized bed, a multiple hearth, or a flash/pneumatic conveyor. Otherwise, use a jacketed spiral conveyor.

Heuristic 34: Use a fan to raise the gas pressure from atmospheric pressure to as high as 40 inches water gauge (10.1 kPa gauge or 1.47 psig). Use a blower or compressor to raise the gas pressure to as high as 206 kPa gauge or 30

psig. Use a compressor or a staged compressor system to attain pressures greater than 206 kPa gauge or 30 psig.

Heuristic 35: Estimate the theoretical adiabatic horsepower (THp) for compressing a gas.

Heuristic 36: Estimate the number of gas compression stages, N .

Heuristic 37: For heads up to 3,200 ft and flow rates in the range of 10 to 5,000 gpm, use a centrifugal pump. For high heads up to 20,000 ft and flow rates up to 500 gpm, use a reciprocating pump. Less common are axial pumps for heads up to 40 ft for flow rates in the range of 20 to 100,000 gpm and rotary pumps for heads up to 3,000 ft for flow rates in the range of 1 to 1,500 gpm.

Heuristic 38: For liquid flow, assume a pipeline pressure drop of 2 psi/100 ft of pipe and a control valve pressure drop of at least 10 psi. For each 10-ft rise in elevation, assume a pressure drop of 4 psi.

Heuristic 39: Estimate the theoretical horsepower (THp) for pumping a liquid.

Heuristic 40: Consider the use of an expander for reducing the pressure of a gas or a pressure-recovery turbine for reducing the pressure of a liquid when more than 20 Hp and 150 Hp, respectively, can be recovered.

Heuristic 41: Estimate the theoretical adiabatic horsepower (THp) for expanding a gas.

Heuristic 42: Estimate the theoretical horsepower (THp) for reducing the pressure of a liquid.

Heuristic 43: To increase the pressure of a stream, pump a liquid rather than compress a gas, unless refrigeration is needed.

Heuristic 44: Estimate in leakage of air.

Heuristic 45: To reduce the amount of gas sent to the vacuum system if its temperature is greater than 100°F, add a condenser using cooling water before the vacuum system. The gas leaving the condenser will be at a dew-point temperature of 100°F at the vacuum pressure.

Heuristic 46: For pressures down to 10 torr and gas flow rates up to 10,000 ft³/min at the inlet to the vacuum system, use a liquid-ring vacuum pump. For pressures down to 2 torr and gas flow rates up to 1,000,000 ft³/min at the inlet to the vacuum system, use a steam-jet ejector system (one-stage for 100 to 760 torr, two-stage for 15 to 100 torr, and three-stage for 2 to 15 torr). Include a direct-contact condenser between stages.

Heuristic 47: For a three-stage steam-jet ejector system used to achieve a vacuum of 2 torr, 100 pounds of 100 psig steam per pound of gas are required.

Heuristic 48: If the solid particles are small in size, low in particle density, and not sticky or abrasive, use pneumatic conveying with air at 1 to 7 ft³/ft³ of solids and 35 to 120 ft/s air velocity for distances up to 400 ft. Otherwise, for sticky and/or abrasive solids of any size and density, use a screw conveyor and/or bucket elevator for distances up to 150 ft.

Heuristic 49: Crushing of coarse solids. Use a jaw crusher to reduce lumps of hard, abrasive, and/or sticky materials of 4 inches to 3 feet in diameter to slabby particles of 1 to 4 inches in size. Use a gyratory crusher to reduce slabby materials of 8 inches to 6 feet in size to rounded particles of 1 to 10 inches in diameter. Use a cone crusher to reduce less hard and less sticky materials of 2 inches to 1 foot in diameter to particles of 0.2 inch (4 mesh) to 2 inches in diameter.

Heuristic 50: Grinding to fine solids. Use a rod mill to take particles of intermediate hardness as large as 20 mm and reduce them to particles in the range of 10 to 35 mesh. Use a ball mill to reduce particles of low to intermediate hardness of 1 to 10 mm in size to very small particles of less than 140 mesh.

Heuristic 51: Particle-size enlargement. Use compression with rotary compression machines to convert powders and granules into tablets of up to 1.5 inches in diameter. Use extruders with cutters to make pellets and wafers from pastes and melts. Use roll compactors to produce sheets from finely divided materials; the sheets are then cut into any desired shape. Use rotating drum granulators and rotary disk granulators with binders to produce particles in the size range of 2 to 25 mm.

Heuristic 52: Size separation of particles. Use a grizzly of spaced, inclined, vibrated parallel bars to remove large particles greater than 2 inches in diameter

Heuristic 53: Use a cyclone separator to remove, from a gas, droplets or solid particles of diameter down to 10 microns (0.01 mm). Use a hydroclone separator to remove, from a liquid, insoluble liquid droplets or solid particles of diameter down to 5 microns (0.005 mm). However, small amounts of entrained liquid droplets are commonly removed from gases by vertical knock-out drums equipped with mesh pads to help coalesce the smallest droplets.

The following objectives are studied

1. Understand the importance of selecting reaction paths that do not involve toxic or hazardous chemicals, and when unavoidable, to reduce their presence by shortening residence times in the process units and avoiding their storage in large quantities.
2. Be able to distribute the chemicals, when generating a process flowsheet, to account for the presence of inert species, to purge species that would otherwise build up to unacceptable concentrations, to achieve a high selectivity to the desired products, and to accomplish, when feasible, reactions and separations in the same vessels (e.g., reactive distillations).
3. Be able to apply heuristics in selecting separation processes to separate liquids, vapours, vapor-liquid mixtures, and other operations involving the processing of solid particles, including the presence of liquid and/or vapor phases.

4. Be able to distribute the chemicals, by using excess reactants, inert diluents, and cold (or hot) shots, to remove the exothermic (supply the endothermic) heats of reaction. These distributions can have a major impact on the resulting process integration.
5. Understand the advantages, when applicable, of pumping a liquid rather than compressing a vapor.



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UNIT – IV – Process Engineering – SCHA1702

A feed separation system may be required to purify the reactor feed(s) by removing catalyst poisons and inert species, especially if they are present as a significant percentage of the feed. An effluent separation system, which follows the reactor system and is almost always required, recovers unconverted reactants (in gas, liquid, and/or solid phases) for recycle to the reactor system and separates and purifies products and by products. Where separations are too difficult, purge streams are used to prevent build up of certain species in recycle streams. Processes that do not involve a reactor system also utilize separation operations if the feed is a mixture that requires separation. Frequently, the major investment and operating costs of a process will be those costs associated with the separation equipment, rather than with the chemical reactor(s).

4.1 Feed Separation System

the combined feed to a reactor section may consist of one or more feed streams and one or more recycle streams when conversion of reactants is incomplete. When a feed separation system is needed and more than one feed enters the process, it is usually preferable to provide separate separation operations for the individual feed streams before mixing them with each other and with any recycle streams. Some industrial examples of chemical processes that require a feed separation system are:

1. Production of polypropylene from a feed of propylene and propane. Propane, which is not involved in the propylene polymerization reaction, is removed from the propylene by distillation.
2. Production of acetaldehyde by the dehydrogenation of ethanol using a chromium-copper catalyst. If the feed is a dilute solution of ethanol in water, distillation is used to concentrate the ethanol to the near-azeotrope composition (89.4 mol% ethanol at 1 atm) before it enters the reactor.
3. Production of formaldehyde by air-oxidation of methanol using a silver catalyst. The entering air is scrubbed with aqueous sodium hydroxide to remove any SO₂ and CO₂, which are catalyst poisons.
4. Production of vinyl chloride by the gas-phase reaction of HCl and acetylene with a mercuric chloride catalyst. Small amounts of water are removed from both feed gases by adsorption to prevent corrosion of the reactor vessel and acetaldehyde formation.
5. Production of phosgene by the gas-phase reaction of CO and chlorine using an activated carbon catalyst. Both feed gases are treated to remove oxygen, which poisons the catalyst;

sulfur compounds, which form sulfur chlorides; hydrogen, which reacts with both chlorine and phosgene to form HCl; and water and hydrocarbons, which also form HCl.

4.2 Phase Separation of Reactor Effluent

The reactor effluent may be a heterogeneous (two or more phases) mixture, but most often is a homogeneous (single-phase) mixture. When the latter, it is often advantageous to change the temperature and/or (but less frequently) the pressure to obtain a partial separation of the components by forming a heterogeneous mixture of two or more phases. Following the change in temperature and/or pressure, phase equilibrium is rapidly attained, resulting in the following possible phase conditions of the reactor effluent, where two liquid phases may form (phase splitting) when both water and hydrocarbons are present in the reactor effluent. Process simulators can readily estimate the amounts and compositions of the phases in equilibrium by an isothermal (two-phase)-flash calculation, provided that solids are not present. When the possibility of two liquid phases exists, it is necessary to employ a three-phase flash model, rather than the usual two-phase flash model. The three-phase model considers the possibility that a vapor phase may also be present, together with two liquid phases.

In the absence of solids, the resulting phases are separated, often by gravity, in a flash vessel for the V-L case, or in a decanter for the V-L1-L2 or L1-L2 cases. For the latter two cases, centrifugal force may be employed if gravity settling is too slow because of small liquid-density differences or high liquid viscosities. If solids are present with one or two liquid phases, it is not possible to separate completely the solids from the liquid phase(s). Instead, a centrifuge or filter is used to deliver a wet cake of solids that requires further processing to recover the liquid and dry the solids.

Each exiting phase is either recycled to the reactor, purged from the system, or, most often, sent to separate vapor, liquid, or slurry separation systems. The effluents from these separation systems are products, which are sent to storage; by products, which also leave the process; reactor-system recycle streams, which are sent back to the reactor; or separation-system recycle streams, which are sent to one of the other separation systems. Purges and by products are either additional valuable products, which are sent to storage; fuel by products, which are sent to a fuel supply or storage system; and/or waste streams, which are sent to waste treatment, incineration, or landfill.

Consider the following examples of phase-equilibria calculations for industrial reactor effluents:

1. Vapor-liquid case. The reactor effluent for a toluene hydrodealkylation process, of the type discussed in Section 5.3, is a gas at 1; 150F and 520 psia. When brought to 100F at say 500 psia by a series of heat exchangers, the result is a vapor phase in equilibrium with a single liquid phase.

4.3 Industrial Separation Operations

Following phase separation, the individual vapor, liquid, solids, and/or slurry streams are sent to individual separation systems, the most common of which is the liquid separation system. When the feed to a vapor or liquid separation system is a binary mixture, it may be possible to select a separation method that can accomplish the separation task in just one piece of equipment. In that case, the separation system is relatively simple. More commonly, however, the feed mixture involves more than two components. Although some progress is being made in devising multicomponent separation systems involving a single piece of equipment, most systems involve a number of units in which the separations are sequenced, with each unit separating its feed stream into two effluent streams of different composition. The separation in each piece of equipment (unit) is made between two components designated as the key components for that particular separation unit. Each effluent is either a final product or a feed to another separation device. The synthesis of a multicomponent separation system can be very complex because it involves not only the selection of the separation method(s), but also the manner in which the pieces of separation equipment are sequenced.

As an example of the complexity of a multicomponent separation system, consider the synthesis of a separation system for the recovery of butenes from a C₄ concentrate from the catalytic dehydrogenation of n-butane. The specifications for the separation process are taken from Hendry and Hughes (1972). The process feed, which contains propane, 1-butene, n-butane, trans-2-butene, cis-2-butene, and n-pentane, is to be separated into four fractions: (1) a propane-rich stream containing 99% of the propane in the feed, (2) an n-butane-rich stream containing 96% of the nC₄ in the feed, (3) a stream containing a mixture of the three butenes, at 95% recovery, and (4) an n-pentane-rich stream containing 98% of the nC₅ in the feed. The C₃ and

nC5 streams are final products, the nC4 stream is recycled to the catalytic dehydrogenation reactor, and the butenes stream is sent to another dehydrogenation reactor to produce butadienes. Many different types of separation devices and sequences thereof can accomplish the separations specified in Figure 8.6. In general, the process design engineer seeks the most economical system. One such system, based on mature technology and the availability of inexpensive energy. The system involves two separation methods, distillation and extractive distillation. The process feed from the butane dehydrogenation unit is sent to a series of two distillation columns (1-butene columns, C-1A and C-1B), where the more volatile propane and 1-butene are removed as distillate and then separated in a second distillation column (depropanizer, C-2) into propane and 1-butene. Distillation unit C-1 consists of two columns because 150 trays are required, which are too many for a single column (since the tray spacing is typically 2 ft, giving a 300-ft high tower, while most towers do not exceed 200 ft for structural reasons). The bottoms from unit C-1A, which consists mainly of n-butane, the 2-butene isomers, and nC5, is sent to another distillation column (deoiler, C-3), where nC5 product is removed as bottoms. The distillate stream from unit C-3 cannot be separated into nC4-rich and 2-butenes-rich streams economically by ordinary distillation because the relative volatility is only about 1.03. Extractive distillation with a solvent of 96% furfural in water, which enhances the relative volatility to about 1.17. The separation occurs in columns C-4A and C-4B, with nC4 taken off as distillate. The bottoms is sent to a furfural stripper (C-5), where the solvent is recovered and recycled to unit C-4 and the 2-butenes are recovered as distillate. The 1-butene and 2-butenes streams are mixed and sent to a butenes dehydrogenation reactor. Practical and economical, it does involve the separation of 1-butene from the 2-butenes. Perhaps another sequence could avoid this unnecessary separation.

There should be given to separating the feed stream into two phases by some mechanical means, and then sending the separated phases to different separation units, each appropriate for the phase condition of the stream. The separation of a feed mixture into streams of differing chemical compositions is achieved by forcing individual species into different spatial locations. This is accomplished by any one or a combination of four common industrial techniques: (1) the creation by heat transfer, shaft work, or pressure reduction of a second phase; (2) the introduction into the system of a second fluid phase; (3) the addition of a solid phase on which selective adsorption can occur; and (4) the placement of a selective membrane barrier. Unlike the mixing of chemical species, which is a spontaneous process, the separation of a mixture of chemicals requires an expenditure of some form of energy. In the first technique,

no other chemicals are added to the feed mixture and the separation is achieved by an energy-separating agent (ESA), usually heat transfer, which causes the formation of a second phase. The components are separated by differences in volatility, thus causing each species to favour one phase over another. In the second technique, a second phase is added to the separation unit in the form of a solvent as a mass-separating agent (MSA) that selectively dissolves or alters the volatility of certain species of the mixture. A subsequent separation step is usually required to recover the solvent for recycle. The third technique involves the addition of solid particles that selectively adsorb certain species of the mixture. Subsequently, the particles must be treated by another separation method to recover the adsorbed species and regenerate the adsorbent for further use. Thus, the particles act as an MSA. The fourth technique imposes a barrier that allows the permeation of some species over others. A mechanical energy loss accompanies the permeation. Thus, this technique involves an ESA. For all four techniques, mass transfer controls the rate of migration of species from one phase to another. Except for the fourth technique, the extent of mass transfer is limited by thermodynamic equilibrium between the phases. In the case of membrane separations, the exiting phases do not approach equilibrium; rather the separation occurs strictly because of differences in the rates of permeation through the membrane.

4 . 4 Criteria For Selection Of Separation Methods

The development of a separation process requires the selection of (1) separation methods, (2) ESAs and/or MSAs, (3) separation equipment, (4) the optimal arrangement or sequencing of the equipment, and (5) the optimal operating conditions of temperature and pressure for the equipment.

When the process feed is a binary mixture and the task is to separate that mixture into two products, a single separation device may suffice if an ESA is used. If an MSA is necessary, an additional separation device will be required to recover the MSA for recycle. For a multicomponent feed that is to be separated into nearly pure components and/or one or more multicomponent products, more than one separation device is usually required. Not only must these devices be selected, an optimal arrangement of the devices must be sought. In devising such a separation sequence, it is preferable not to separate components that must be blended later to form desired multicomponent products. However, many exceptions exist to this rule.

A six component mixture is separated into four products, one of which contains 1-butene and cis- and trans-2-butene. The separation of 1-butene from the 2-butenes and subsequent blending to obtain the desired olefin mixture. The unnecessary separation is carried out because the volatility of n-butane is intermediate between that of 1-butene and the two 2-butene isomers. In a multicomponent separation process, each separation operation generally separates between two components, in which case the minimum number of operations is one less than the number of products. However, there are a growing number of exceptions to this rule, and cases are described later for which a single separation operation may produce only a partial separation.

4.5 Reason for the Separation as a Criterion

A final consideration in the selection of a separation method is the reason for the separation. Possible reasons are (1) purification of a species or group of species, (2) removal of undesirable constituents, and (3) recovery of constituents for subsequent processing or removal. In the case of purification, the use of an MSA method may avoid exposure with an ESA method to high temperatures that may cause decomposition. In some cases, removal of undesirable species together with a modest amount of desirable species may be economically acceptable. Likewise, in the recovery of constituents for recycle, a high degree of separation from the product(s) may not be necessary.

4.6 Selection Of Equipment

Only a very brief discussion of equipment for separation operations is presented here. Much more extensive presentations, including drawings and comparisons, are given in Perry's Chemical Engineers' Handbook (Green and Perry, 2008) and by Kister (1992), Walas (1988), Seader and Henley (2006), and in Visual Encyclopedia of Chemical Engineering Equipment for MacIntosh and Windows 95/NT by Montgomery, as described at www.engin.umich.edu/labs/mel/equipflyer/equip.html. In general, equipment selection is based on stage or mass transfer efficiency, pilot-plant tests, scale-up feasibility, investment and operating cost, and ease of maintenance.

4.7 Absorption, Stripping, and Distillation

For absorption, stripping, and all types of distillation (i.e., vapor–liquid separation operations), either trayed or packed columns are used. Trayed columns are usually preferred for initial

installations, particularly for columns 3 ft or more in diameter. However, packed columns should be given serious consideration for operation under vacuum or where a low-pressure drop is desired. Other applications favouring packed columns are corrosive systems, foaming systems, and cases where low liquid holdup is desired. Packing is also generally specified for revamps. Applications favouring trayed columns are feeds containing solids, high liquid-to-gas ratios, large-diameter columns, and where operation over a wide range of conditions is necessary. The three most commonly used tray types are sieve, valve, and bubble-cap. However, because of high cost, the latter is specified only when a large liquid holdup is required on the tray, for example, when conducting a chemical reaction simultaneously with distillation. Sieve trays are the least expensive and have the lowest pressure drop per tray, but they have the narrowest operating range (turndown ratio). Therefore, when flexibility is required, valve trays are a better choice. Many different types of packings are available. They are classified as random or structured. The latter are considerably more expensive than the former, but the latter have the lowest pressure drop, the highest efficiency, and the highest capacity compared to both random packings and trays. For that reason, structured packings are often considered for column revamps.

4.8 Liquid-Liquid Extraction

For liquid-liquid extraction, an even greater variety of equipment is available, including multiple mixer-settler units or single counter current flow columns with or without mechanical agitation. Very compact, but expensive, centrifugal extractors are also available. When the equivalent of only a few theoretical stages is required, mixer-settler units may be the best choice because efficiencies approaching 100% are achievable in each unit. For a large number of stages, columns with mechanical agitation may be favoured. Packed and perforated tray columns can be very inefficient and are not recommended for critical separations.

4.9 Membrane Separation

Most commercial membrane separations use natural or synthetic glassy or rubbery polymers. To achieve high permeability and selectivity, nonporous materials are preferred with thicknesses ranging from 0.1 to 1.0 micron, either as a surface layer or film onto or as part of much thicker asymmetric or composite membrane materials, which are fabricated primarily into spiral-wound and hollow fiber type modules to achieve a high ratio of membrane surface area to module volume.

4.10 Adsorption

For commercial applications, an adsorbent must be chosen carefully to give the required selectivity, capacity, stability, strength, and regenerability. The most commonly used adsorbents are activated carbon, molecular-sieve carbon, molecular-sieve zeolites, silica gel, and activated alumina. Of particular importance in the selection process is the adsorption isotherm for competing solutes when using a particular adsorbent. Most adsorption operations are conducted in a semicontinuous cyclic mode that includes a regeneration step. Batch slurry systems are favoured for small-scale separations, whereas fixed-bed operations are preferred for large-scale separations.

4.11 Leaching

Equipment for leaching operations is designed for either batchwise or continuous processing. For rapid leaching, it is best to reduce the size of the solids by grinding or slicing. The solids are contacted by the solvent using either percolation or immersion. A number of different patented devices are available.

4.12 Crystallization

Crystallization operations include the crystallization of an inorganic compound from an aqueous solution (solution crystallization) and the crystallization of an organic compound from a mixture of organic chemicals (melt crystallization). On a large scale, solution crystallization is frequently conducted continuously in a vacuum evaporating draft-tube baffled crystallizer to produce crystalline particles, whereas the falling-film crystallizer is used for melt crystallization to produce a dense layer of crystals.

4.13 Drying

A number of factors influence the selection of a dryer from the many different types available. These factors are dominated by the nature of the feed, whether it be granular solids, a paste, a slab, a film, a slurry, or a liquid. Other factors include the need for agitation, the type of heat source (convection, radiation, conduction, or microwave heating), and the degree to which the material must be dried. The most commonly employed continuous dryers

include tunnel, belt, band, turbo-tray, rotary, steam-tube rotary, screw-conveyor, fluidized-bed, spouted-bed, pneumatic-conveyor, spray, and drum dryers.

4.14 Sequencing Of Ordinary Distillation Columns For The Separation Of Nearly Ideal Fluid Mixtures

Multicomponent mixtures are often separated into more than two products. Although one piece of equipment of complex design might be devised to produce all the desired products, a sequence of two-product separators is more common.

For nearly ideal feeds such as hydrocarbon mixtures and mixtures of a homologous series, for example, alcohols, the most economical sequence will often include only ordinary distillation columns, provided that the following conditions hold:

1. The relative volatility between the two selected key components for the separation in each column is >1.05 .
2. The reboiler duty is not excessive. An example of an excessive duty occurs in the distillation of a mixture with a low relative volatility between the two key components, where the light key component is water, which has a very high heat of vaporization.
3. The tower pressure does not cause the mixture to approach its critical temperature.
4. The overhead vapor can be at least partially condensed at the column pressure to provide reflux without excessive refrigeration requirements.
5. The bottoms temperature at the tower pressure is not so high that chemical decomposition occurs.
6. Azeotropes do not prevent the desired separation.
7. Column pressure drop is tolerable, particularly if operation is under vacuum.

4.15 Column Pressure and Type of Condenser

During the development of distillation sequences, it is necessary to make at least preliminary estimates of column operating pressures and condenser types (total or partial). The estimates are facilitated by the use of the algorithm which is conservative. Assume that cooling water is available at 90F, sufficient to cool and condense a vapor to 120F. The bubble-point pressure is calculated at 120F for an estimated distillate composition. If the computed pressure is less than 215 psia, use a total condenser unless a vapor distillate is required, in which case use a partial condenser. If the pressure is less than 30 psia, set the condenser pressure to 30 psia and

avoid near-vacuum operation. If the distillate bubble-point pressure is greater than 215 psia, but less than 365 psia, use a partial condenser. If it is greater than 365 psia, determine the dew point pressure for the distillate as a vapor. If the pressure is greater than 365 psia, operate the condenser at 415 psia with a suitable refrigerant in place of cooling water. For the selected condenser pressure, add 10 psia to estimate the bottoms pressure, and compute the bubble-point temperature for an estimated bottoms composition. If that temperature exceeds the decomposition or critical temperature of the bottoms, reduce the condenser pressure appropriately.

4.16 Number of Sequences of Ordinary Distillation Columns

Initial consideration is usually given to a sequence of ordinary distillation columns, where a single feed is sent to each column and the products from each column number just two, the distillate and the bottoms. For example, consider a mixture of benzene, toluene, and biphenyl. Because the normal boiling points of the three components (80.1, 110.8, and 254.9°C, respectively) are widely separated, the mixture can be conveniently separated into three nearly pure components by ordinary distillation. A common process for separating this mixture is the sequence of two ordinary distillation columns. In the first column, the most volatile component, benzene, is taken overhead as a distillate final product. The bottoms is a mixture of toluene and biphenyl, which is sent to the second column for separation into the two other final products: a distillate of toluene and a bottoms of biphenyl, the least volatile component.

Even if a sequence of ordinary distillation columns is used, not all columns need give nearly pure products. For example, Figure 8.10b shows a distillation sequence for the separation of a mixture of ethylbenzene, p-xylene, m-xylene, and o-xylene into only three products: nearly pure ethylbenzene, a mixture of p- and m-xylene, and nearly pure o-xylene. The para and meta isomers are not separated because the normal boiling points of these two compounds differ by only 0.8°C, making separation by distillation impractical.

Note that it takes a sequence of two ordinary distillation columns to separate a mixture into three products. Furthermore, other sequences can produce the same final products. For example, the separation of benzene, toluene, and biphenyl, can also be achieved by removing biphenyl as bottoms in the first column, followed by the separation of benzene and toluene in the second column. However, the separation of toluene from benzene and biphenyl by ordinary distillation in the first column is impossible, because toluene is intermediate in volatility. Thus, the number of possible sequences is limited to two for this case of the separation of a ternary mixture into three nearly pure products.

Now consider the more general case of the synthesis of all possible ordinary distillation sequences for a multi-component feed that is to be separated into P final products that are nearly pure components and/or multicomponent mixtures. The components in the feed are ordered by volatility, with the first component being the most volatile. This order is almost always consistent with that for normal boiling point if the mixture forms nearly ideal liquid solutions. Assume that the order of volatility of the components does not change as the sequence proceeds. Furthermore, assume that any multicomponent products contain only components that are adjacent in volatility. For example, suppose that the previously cited mixture of benzene, toluene, and biphenyl is to be separated into toluene and a multicomponent product of benzene and biphenyl. With ordinary distillation, it would be necessary first to produce products of benzene, toluene, and biphenyl, and then blend the benzene and biphenyl.

4.17 Marginal Vapor Rate Method

When application of the above heuristics for sequencing ordinary distillation columns is uncertain or conflicting results are obtained, it is preferable to employ sequencing methods that rely on column design and, in some cases, cost estimation. Exhaustive search to calculate the annualized cost of every sequence can determine the optimal sequence, provided that column-operating conditions are optimized, and may be justified for sequences involving just three or possibly four products. However, less rigorous methods are available that can produce good, although not always optimal, sequences. These methods, which attempt to reduce the search space, include those of Hendry and Hughes (1972), Rodrigo and Seader (1975), Gomez and Seader (1976), Seader and Westerberg (1977), and the marginal vapor rate (MV) method of Modi and Westerberg (1992). The latter method outperforms the other methods and can be applied without the necessity of complete column designs and calculations of costs.

For a given split between two key components, Modi and Westerberg (1992) consider the difference in costs between the separation in the absence of non key components and the separation in the presence of non key components, defining this difference as the marginal annualized cost (MAC). They show that a good approximation of MAC is the MV, which is the corresponding difference in molar vapor rate passing up the column. The sequence with the minimum sum of column MVs is selected. The good approximation is due to the fact that vapor rate is a good measure of cost because it is a major factor in determining column diameter as well as reboiler and condenser areas (thus, column and heat-exchanger capital costs) and reboiler and condenser duties (thus, heat-exchanger annual operating costs).

4.18 Sequencing Of Operations For The Separation Of Nonideal Fluid Mixtures

When a multicomponent fluid mixture is nonideal, its separation by a sequence of ordinary distillation columns will not be technically and/or economically feasible if relative volatilities between key components drop below 1.05 and, particularly, if azeotropes are formed. For such mixtures, separation is most commonly achieved by sequences comprised of ordinary distillation columns, enhanced distillation columns, and/or liquid–liquid extraction equipment. Membrane and adsorption separations can also be incorporated into separation sequences, but their use is much less common. Enhanced distillation operations include extractive distillation, homogeneous azeotropic distillation, heterogeneous azeotropic distillation, pressure-swing distillation, and reactive distillation. These operations are considered in detail in Perry's Chemical Engineers' Handbook (Green and Perry, 2008) and by Seader and Henley (2006), Stichlmair and Fair (1998), and Doherty and Malone (2001).

In many processes involving oxygenated organic compounds such as alcohols, ketones, ethers, and acids, often in the presence of water, distillation separations are complicated by the presence of azeotropes. Close-boiling mixtures of hydrocarbons (e.g., benzene and cyclohexane, whose normal boiling points only differ by 1°F) can also form azeotropes. For these and other mixtures, special attention must be given to the distillation boundaries in the composition space that confine the compositions for any one column to lie within a bounded region of the composition space. To introduce these boundaries, leading to approaches for the synthesis of separation trains, several concepts concerning azeotropes and residue curves and distillation lines are reviewed in the subsections that follow.

4.19 Azeotropy

Azeotrope is an ancient Greek word that is translated “to boil unchanged,” meaning that the vapor emitted has the same composition as the liquid (Swietoslawski, 1963). When classifying the many azeotropic mixtures, it is helpful to examine their deviations from Raoult's law (Lecat, 1918). When two or more fluid phases are in physical equilibrium, the chemical potential, fugacity, or activity of each species is the same in each phase. They are close boiling mixtures.

Of great practical interest is the effect of distillation boundaries on the operation of distillation towers. To summarize a growing body of literature, it is well established that the compositions of a distillation tower operating at total reflux cannot cross the distillation-line boundaries,

except under unusual circumstances, where these boundaries exhibit a high degree of curvature. This provides the total-reflux bound on the possible (feasible) compositions for the distillate and bottoms products.

4.20 Heterogeneous Distillation

In heterogeneous azeotropic distillation, an entrainer is utilized that concentrates in the overhead vapor and, when condensed, causes the formation of a second liquid phase that can be decanted and recirculated to the tower as reflux. The other liquid phase as well as the bottoms are the products from the distillation. This is possible when the entrainer forms a heterogeneous azeotrope with one or more of the species in the feed. One possible configuration, with an accompanying triangular diagram for the dehydration of ethanol using toluene as an entrainer. In Column C-1, the feed is preconcentrated in ethanol. Column C-2 is the azeotropic tower. Unfortunately, both products B1 and B2 are bottoms. Ethanol and water form a minimum-boiling azeotrope at 89 mol% ethanol and 1 atm. which were prepared by ASPEN PLUS. Although toluene is the highest-boiling species, it is an appropriate entrainer because it forms minimum-boiling azeotropes with both water and ethanol. Hence, the arrows on the residue curves point toward both the ethanol and water vertices, allowing ethanol to be recovered in a high-purity bottoms product. Since toluene forms a ternary, minimum-boiling, heterogeneous azeotrope, the overhead vapor approaches this composition and condenses into two liquid phases, one rich in toluene and the other rich in water which are separated in the decanter. The former is recycled to the azeotropic tower, while the latter is recycled to the pre concentrator.

When residue curve and distillation-line maps are constructed for heterogeneous systems using process simulation programs, the composition spaces are also divided into regions with simple distillation boundaries. However, the residue curve and distillation-line maps for systems containing heterogeneous azeotropes are far more restricted. Their azeotropic points can only be minimum-boiling saddles or unstable nodes. More importantly, the compositions of the two liquid phases lie within different distillation regions. This unique property, which is not shared by homogeneous systems, enables the decanter to bridge the distillation regions. This is the key that permits the compositions.

4.21 Membrane Separation by Gas Permeation

In gas permeation, the gas mixture is compressed to a high pressure and brought into contact with a very thin membrane to produce two products: (1) a permeate that passes through the membrane and is discharged at a low pressure, and (2) a retentate that does not pass through the membrane and is maintained at close to the high pressure of the feed. The separation factor defined can be applied to gas permeation, when the retentate-side pressure is much greater than the permeate-side pressure, if y is the mole fraction in the permeate and x is the mole fraction in the retentate. The relative volatility is replaced by the ratio of the membrane permeabilities for the two key components of the feed–gas mixture, sometimes called the perm selectivity. Most commercial membranes for gas permeation are non-porous (dense) amorphous or semicrystalline polymers. To pass through such polymers, the gas molecules first dissolve in the polymer and then pass through it by diffusion. Thus, the permeability depends on both solubility and diffusivity in the particular polymer at the conditions of temperature and pressure. The permeability is the product of the solubility and diffusivity. Permeabilities are best determined by laboratory measurements. However, a predictive method given by Barnicki (1991) for a number of glassy and rubbery polymers, which depends on species van der Waals volume and critical temperature, can be applied in the absence of data. In general, gas permeation is commercially feasible when the ratio of permeabilities (perm selectivity) for the two components is greater than 15. However, some processes that require only rough enrichments use membranes having permselectivities of only 5. Commercial applications include the recovery of carbon dioxide from hydrocarbons, the adjustment of the hydrogen-to-carbon monoxide ratio in synthesis gas, the recovery of hydrocarbons from hydrogen, and the separation of air into nitrogen- and oxygen-enriched streams.

4.22 Adsorption

Adsorption differs from the other techniques in that it is a cyclic operation with adsorption and desorption steps. However, adsorption is a very versatile separation technique. To be economical, the adsorbent must be regenerable. This requirement precludes the processing of gas mixtures that contain (1) high-boiling organic compounds, because they are preferentially adsorbed and are difficult to remove during the regeneration part of the cycle, (2) lower-boiling organic compounds that may polymerize on the adsorbent surface, and (3) highly acidic or basic compounds that may react with the adsorbent surface. In some

cases, such compounds can be removed from the gas mixture by guard beds or other methods prior to entry into the adsorption system. Selectivity in adsorption is controlled by (1) molecular sieving or (2) adsorption equilibrium. When components differ significantly in molecular size and/or shape, as characterized by the kinetic diameter, zeolites and carbon molecular-sieve adsorbents can be used to advantage because of the strong selectivity achieved by molecular sieving.

4.23 Absorption

Absorption of components of a gas mixture into a solvent may take place by physical or chemical means. When no chemical reaction between the solute and absorbent occurs (physical absorption), the separation factor α . Thus, if component 1 is to be selectively absorbed, a small value of α is desired. Alternatively, Barnicki and Fair (1992) suggest that consideration of physical absorption should be based on a selectivity, S , defined as the ratio of liquid-phase mole fractions of the two key components in the gas mixture. This selectivity can be estimated from the partial pressures of the two components in the gas feed and their K -values for the given solvent.



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DEPARTMENT OF CHEMICAL ENGINEERING

UNIT – V – Process Engineering – SCHA1702

Unit operations play an important role in the development of chemical processes. They provide building blocks, process segments that can be designed individually and then combined into larger process systems. Unit operations include physical and chemical phenomena such as mass transport, mixing, distillation, separation, heat transfer, evaporation and drying. Many industrial plants include one or more of these elements. In addition, various chemical reactions with special characteristics can be carried out in specialized reactors or sequences of unit operations.

5.1 Transport Of Liquids, Solids And Gases

One of the most basic unit operations is the movement of materials in different forms from one point to another between processes or within process segments. The method of transport depends on whether the material is a liquid, gas or solids. Fluids are usually transported through pipes in which the driving force is a pressure drop created by a pump, compressor, or blower. The description of a fluid transport system must include the operating characteristics of the pump, compressor, or blower expressed as a function of speed of the driving device, pressure drop, pipe dimensions and so forth.

A major difference between liquids and gases is that for most practical purposes most liquids can be assumed to be incompressible. This makes liquid systems much simpler than to analyze gases and liquids in the same manner and account for the differences as a function of the distance between individual practices.

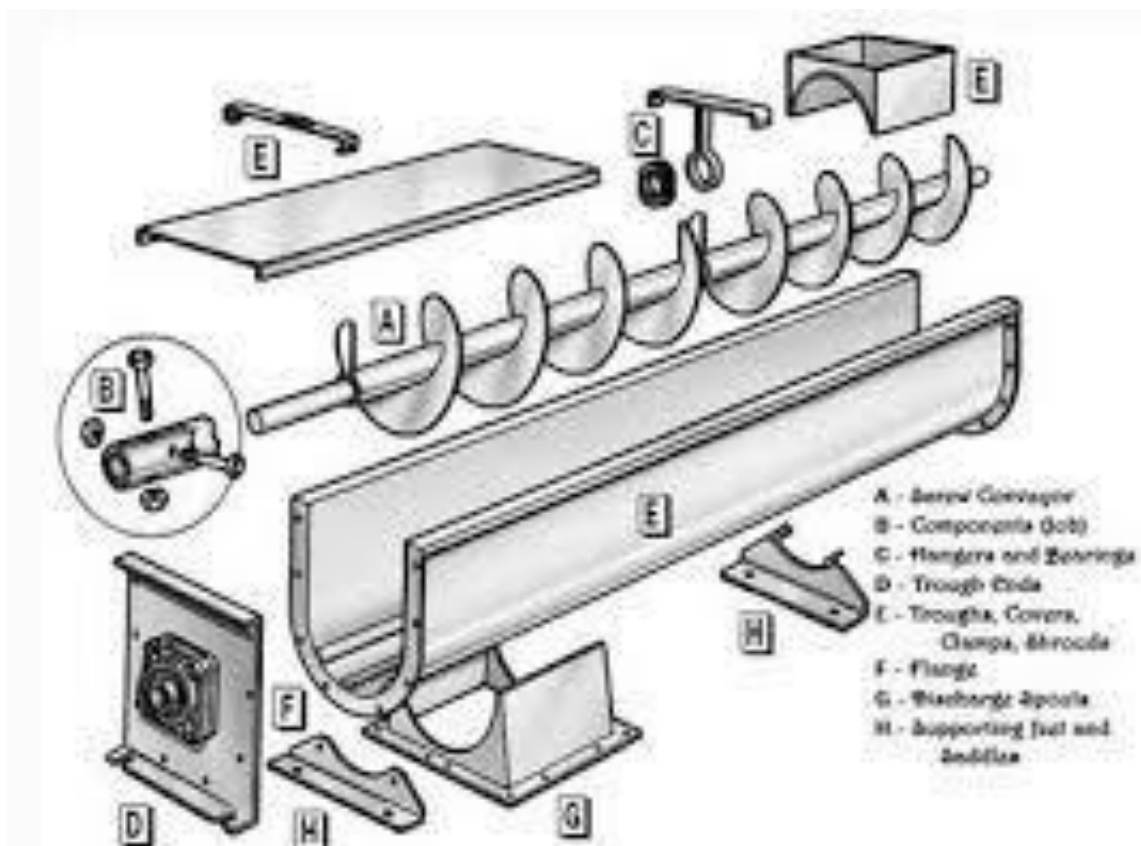
5.2 Compression of gases

Blowers and compressors are often used to provide the pressure differential needed to move gases through chemical processes. Blowers are effective up to pressures of about 0.3 bar, while compressors can develop up to about 4000 bar. A gas compressor is based upon the same principle as a pump that is used for liquids.

5.3 Transport of solids

Many industrial processes must handle bulk solids, often in granular or powdered form. Various devices, such as conveyors, screw augers, vibrating platforms, pneumatic tubes, bucket elevators and so on can be used for transporting and metering these materials.

Automatic control requires that the transport device be controllable over a reasonable range by means of some type of control variable. The screw conveyor shown in figure, varies the flow by varying the speed of the screw. Here, the amount of material allowed to drop from the silo onto the conveyor belt is controlled by the opening of the discharging chute from the silo. Even though, the belt has constant speed, the total material delivered will be controlled. Flow from, the hopper in figure is controlled either by rotation speed of the table or the position of the scraper



5.4 Methods of adjusting particle size of bulk solids

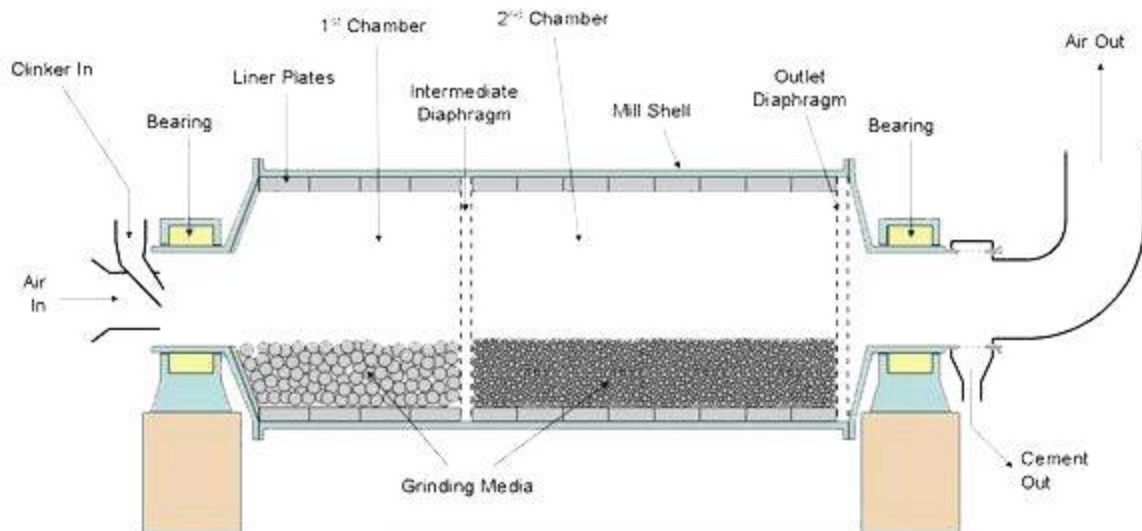
Many industrial processes include operations for reducing the size of the bulk raw materials or intermediate products through crushing, milling or grinding. Other industries use unit processes for increasing particle size through agglomeration, palletizing. Most of these processes must be automatically controlled.

5.5 Continuous ball mill:

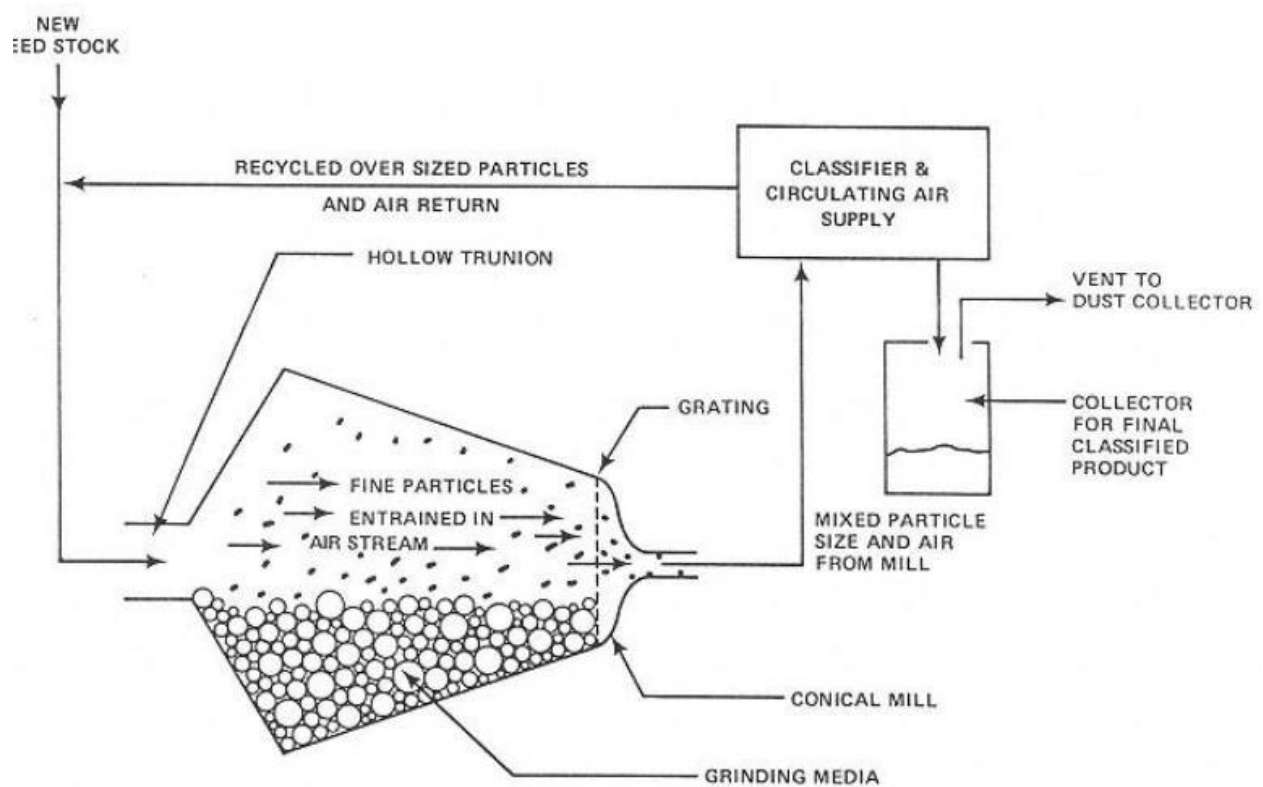
The raw material enters the center of a large rotating cylinder lined with steel or rubber plates. The cylinder contains a large number of steel balls , because of wear and tear , usually have different diameters. The rotation of the cylinder causes the steel balls to rise and fall inside the cylinder, applying a grinding and crushing action on the material. The speed with which the size of the material is reduced depends on many characteristics of both mill and the material. Most important characteristics are

- ☐ Level of the material in the mill
- ☐ Solid – liquid ratio in the case of wet milling process
- ☐ Rotation speed of the mill
- ☐ No. of balls in the mill

The dynamics of a mill depend primarily on whether the mill is operated as a closed circuit system, with a classifier and recycle of the rejects. The mill is followed by a classifier that separates the oversized particles and sends them back to the mill. A step closed circuit process used for wet grinding also. In this system, a primary mill is followed by a rake classifier that returns the larger particles (rejects) to the primary feed, while the fine particles(accepts) are sent to bowl classifier. The rejects from this classifier are sent to another rake classifier that feeds the secondary mill. The accepts from the bowl classifier are sent to a thickening device, often a sedimentation tank.



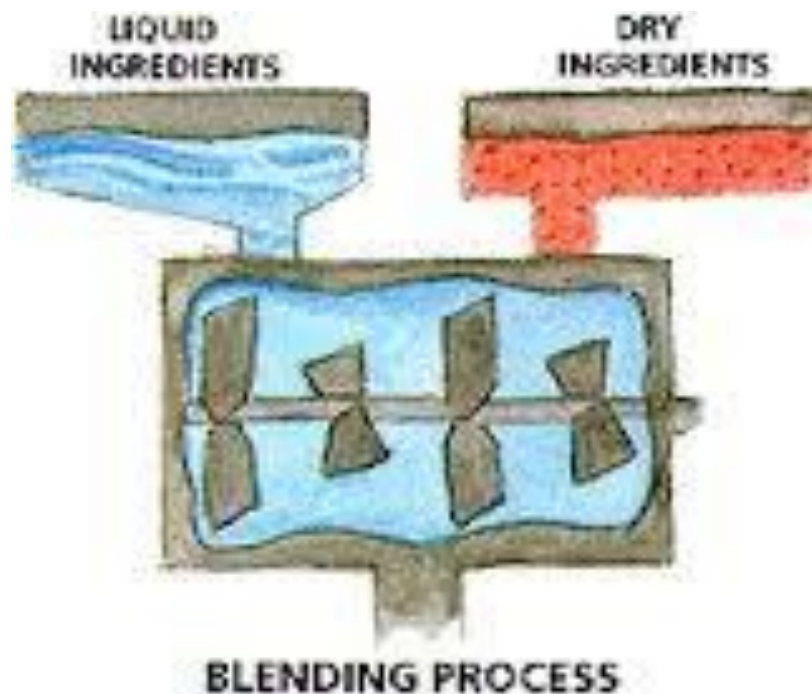
Continuous Ball Mill



5.6 Particle size increase (Agglomeration) of powdered and granulated materials.

Many industrial process require that the raw materials have minimum particle size in order to assure proper processing or chemical reaction. Ex. Reduction of iron ore.

Perhaps, the most common method of forming pellets (granules) is to roll dry powdered materials together with little moisture(the choice of the actual liquid depends upon the material and the use). This action causes the powdered particles to stick together, forming granules of increasing size. Two such processes are shown in figure. This action produces an even distribution of granules up to the desired size. The larger granules will tend to move outward on the plate and eventually fall off the edge, thus undergoing a natural size selection process. The powder and liquid are added and each of the supply streams must be carefully controlled and a possible control variable of granule size is the rotation speed of the disc. The angle of inclination of the disc could also be a control variable.



5.7 Mixing

There are many kinds of mixing operations needed in the process industries and there are nearly as variations of mixing devices and systems. Some liquids are soluble in each other while others are not. Insoluble liquids can be mixed to promote a chemical reaction to heat or cool one of the liquids. Or to form permanent emulsions.. Solids of various types, usually powders or granules, must also be mixed with each other.

Good mixing is defined as , which is actually, the best possible distribution of one material in the other-requires creation of an internal mixing (or transport) velocity high enough to create a high probability of contact between elements of the different materials. The physical form of mixing depends on what is to be mixed. The basic phase possibilities are: gas-gas, gas-liquid, gas-solid, liquid-liquid, liquid-solid, solid-solid.

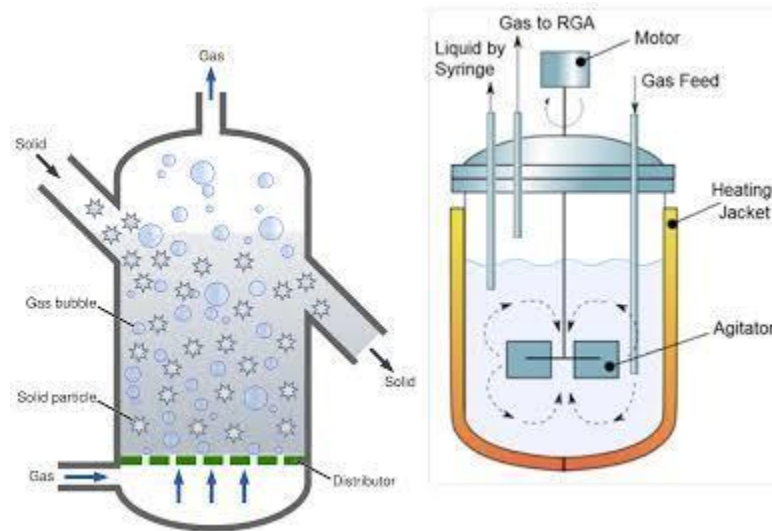
Gas-gas mixing is probably the simplest problem, and the comments regarding liquid-liquid mixing also apply in principle to the mixing of gases. Contact between liquids and gases is important in the following unit operations.

1. Distillation
2. absorption
3. adsorption
4. evaporation
5. humidification
6. de humidification

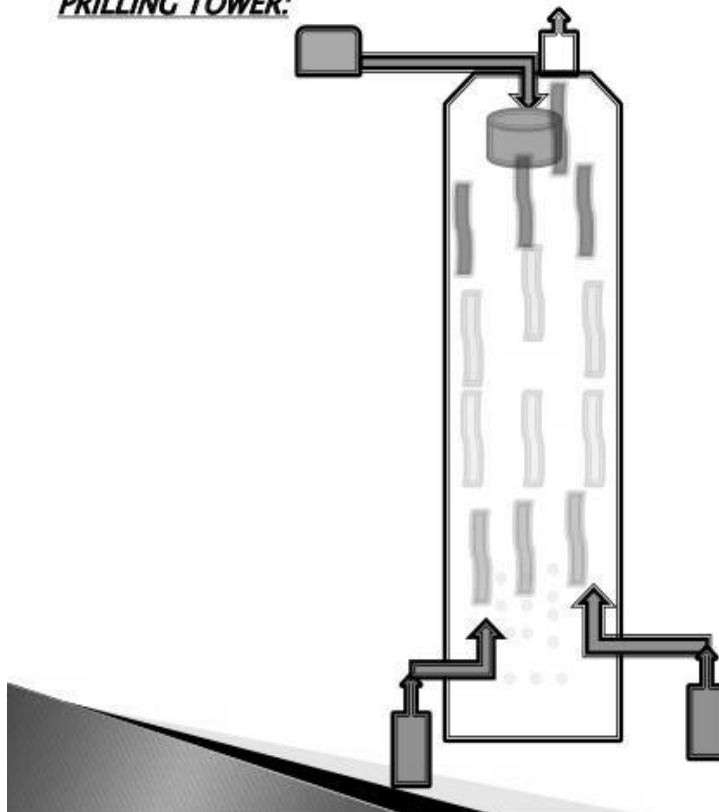
5.8 Mixing of gases and solids

This is especially important in drying and chemical reactions. One very common mixer for this combination is a rotating drum, mounted at a slight angle to the horizontal, in which the solid material is tumbled, preferably counter current to the flow of gas. An increasingly popular and very efficient method is the fluidized bed, where gas at high velocity actually floats the solid.

In this case, the solid circulates in the bed as the gas moves upward. This floating or fluidization provides excellent contact between the solid particles and the gas. A third method is prilling tower.



PRILLING TOWER:



5.9 Liquid- solid mixing

The choice of equipment can be used for liquid – solid mixing will depend on whether the liquid or the solid is the dominant material. For very viscous materials(dominated by the solid), a screw mixer, similar to the familiar kitchen meat grinder The mixing efficiency is strongly dependent on hold up time and internal velocity. If a chemical reaction accompanies the mixing , then the hold up time must be sufficient for the reaction to reach the desired degree of completion.It consists of a silo fitted with a screw conveyor that has the dual function of mixing the materials and in lower section, removing the mixture from silo. A conical screw mixer for mixing various viscous materials is shown in figure

5.10 Separation

The possible combinations that might have to be separated in industrial processes are:

Gas-gas, gas-liquid, gas-solid, liquid-liquid, liquid –solid, solid-solid.

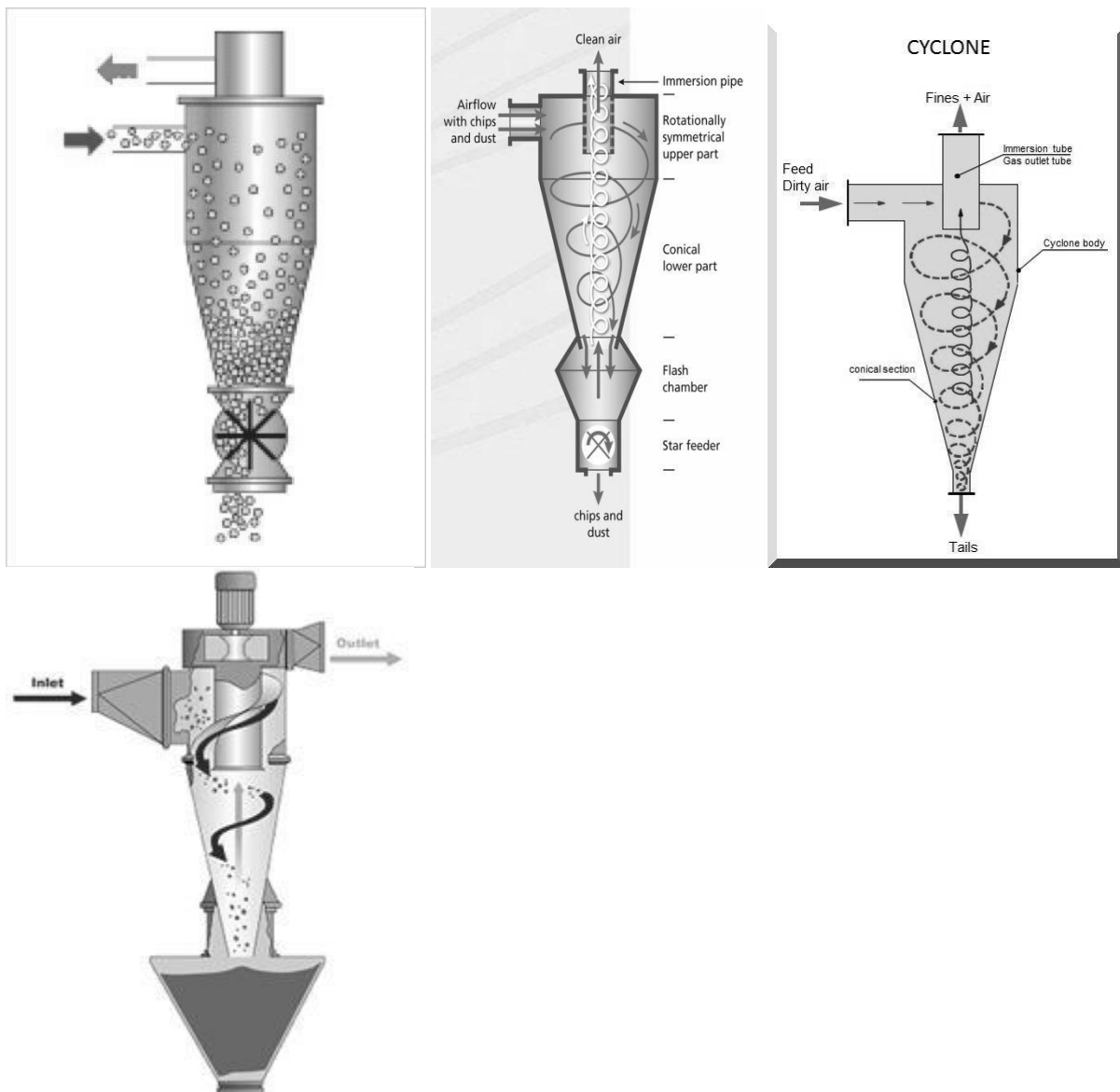
The choice of equipment for separation depends upon the materials to be separate. We can use screens or fiber filters for separating solids from liquids., fiber or electrostatic filters for separating solids from gases and centrifuges for separating solids from gases and liquids, magnetic separators for separating magnetic from non magnetic materials, floatation cells for separating materials with different surface properties.

5.11 Separation of gas from solid:

Separation of gas from solids is required in many processes. One method is drying by means of either separation or sublimation. Another gas/ solids separation process is used for removing dust or dirt from gas. This can be done by means of cyclone separator, a bag filter, scrubbers, or an electrostatic filter.

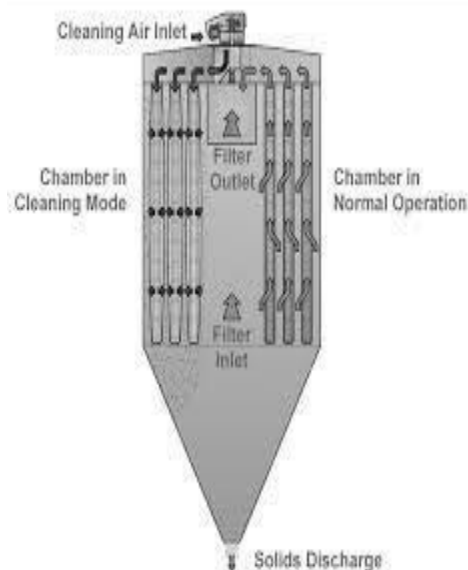
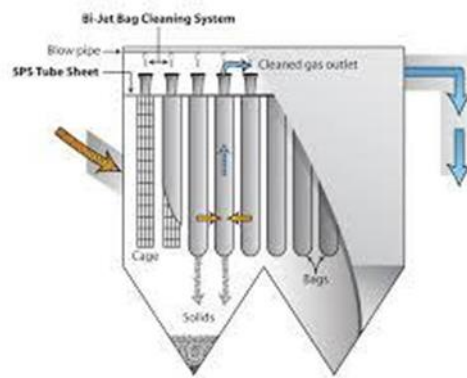
Cyclone separator is probably the most widely used , in this device, gas that contains small particles of dirt or dust that enters the upper part of the cyclone., tangentially to the cyclone wall. Because, they are heavier than the gas, the dirt particles are forced toward the wall. Then, they

fall along the wall and eventually leave the cyclone converter at the bottom. The gas is forced to the center at the bottom, reverses direction and flows upward in the direction and out the top of the cylinder. A cyclone does not have control variables; but can be controlled by manipulating the pressure drop across the cyclone. In practices, a single cyclone does not provide the required degree of separation, it can be followed by additional cyclone stages or separation devices.



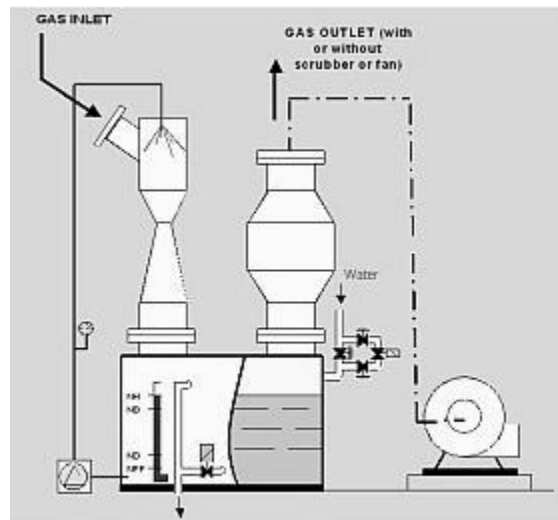
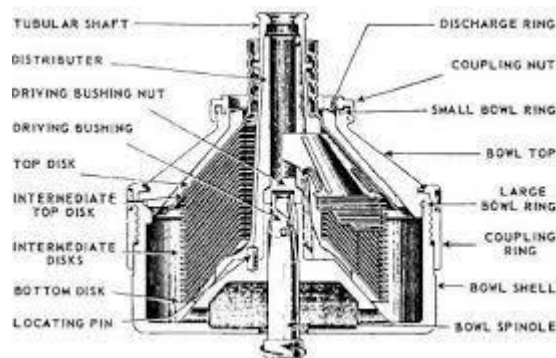
5.12 Bag filters:

A rug is used in bag filter. It is thin , fine- meshed material or it can be made of quick thick filtering material. When thin material is used, the mesh size is usually larger than the size of the particles to be removed. The filtering actions are provided by a filter cake, which is build up of filtered particles on the mesh material. The filter cake will continue to build up until the pressure drop across it, provided by a filter cake, which is a build up of filtered particles on the mesh material. It continue to build up until the pressure drop across it gets high that some of the cake must be removed. Control of the bag filter is generally limited to monitoring the pressure drop across the filter cake and measuring the particle content of the filtered gas.



5.13 Disk centrifuge:

The most common form of centrifuge is shown in figure. The mixture is added at the top ocenter, but it actually enters the centrifuge at the bottom. The liquid rises through a series of conical metal plates that are to be separated by a distance of about 0.3 to 2mm, depending upon the material to be centrifuged. There are about one hundred of these plates, each of which has a number of holes. A centrifuge rotates at very high speed up to about 10000 rpm. The hold up time of a centrifuge is determined by a ratio of the hold up volume to the through put rate for each of the liquid components.

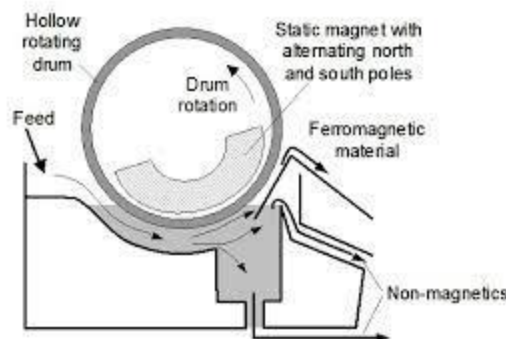


5.14 Scrubbers

The actual lay out of the scrubber system depends upon the method used to atomize the liquid. The solids can be separated from the scrubbing liquid by a filtration process. Cleaning or washing a gas in a scrubber consists of literally washing the solid particles out of the gas by means of a counter current liquid shower, usually water. A scrubber is usually designed to remove finer particles than either a cyclone or a bag filter removes and therefore it is often installed in cascade following those devices if they cannot satisfactorily separate the solid particles from the gas.

5.15 Magnetic Separator

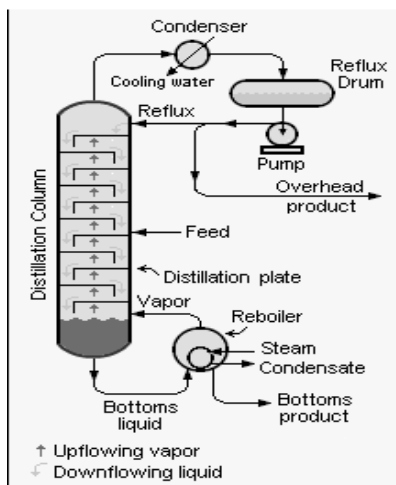
Separation of solid particles on the basis of density or size can also be done by dispersing the solids in a liquid. Separation of solids by magnetic means is widely used in the mining and mineral refining industries. The schematic diagram is shown in figure. A number of fixed permanent magnets mounted inside the drum create a magnetic field that holds the magnetic material. The non magnetic material remains in suspension and leaves the system. The magnetic particles remain on the drum until they leave the field of the last magnet where they will drop and or be scraped off the drum. The efficiency or separation quality of a magnetic separator is characterized by the amount of magnetic materials remaining in the suspension, relative to the amount of non magnetic mater



5.16 Distillation

It is a very Important separation process. Distillation process makes use of the fact that two or more materials can be separated on the basis of their different boiling points. A schematic diagram is shown in figure. Liquid and vapor are in contact with each other at the same temperature and pressure at each tray. Each tray contains a number of holes, each with a cover. Vapor produced by the re boiler enters at the bottom and rises through the column, passing through each tray where it bubbles through the liquid. The liquid moves down through the column, through a space that acts as a liquid seal. The liquid leaves each tray by passing over a barrier that combined with the hydro dynamic conditions in the seal chamber, determines the liquid level on the tray. The holes in the trays are provided to assure good contact between the vapor and the liquid. The resistance to upward flow of the vapor gives the pressure gradient in the column, which is such that the absolute pressure is highest at the bottom and lowest at the top of the column. Likewise, there will be a temperature gradient over the column, with the highest temperature at the bottom and lowest at the top.

In binary distillation, the liquid is assumed to have two components. It is fed into the system at some tray, somewhere between the top and bottom of the column. Because of its weight, the liquid will flow downward from the tray to tray to the bottom of the column, where part of it is evaporated by the re boiler. The reminder of the liquid is removed from the system as bottom product. The vapor that leaves the column at the top is condensed and collected in an accumulator. Some of the liquid from the accumulator is recycled to the column and the remainder is drawn off as top product (distillate)



Distillation columns are used in a very broad range of applications. In sugar industries, the distillation of a mixture of water and different alcohols, produced by fermentation of sugar. Pure oxygen, used for medical purposes is produced by the distillation process. Oil refineries make use of distillation for separating all the petroleum by products.

5.17 Chemical reactor

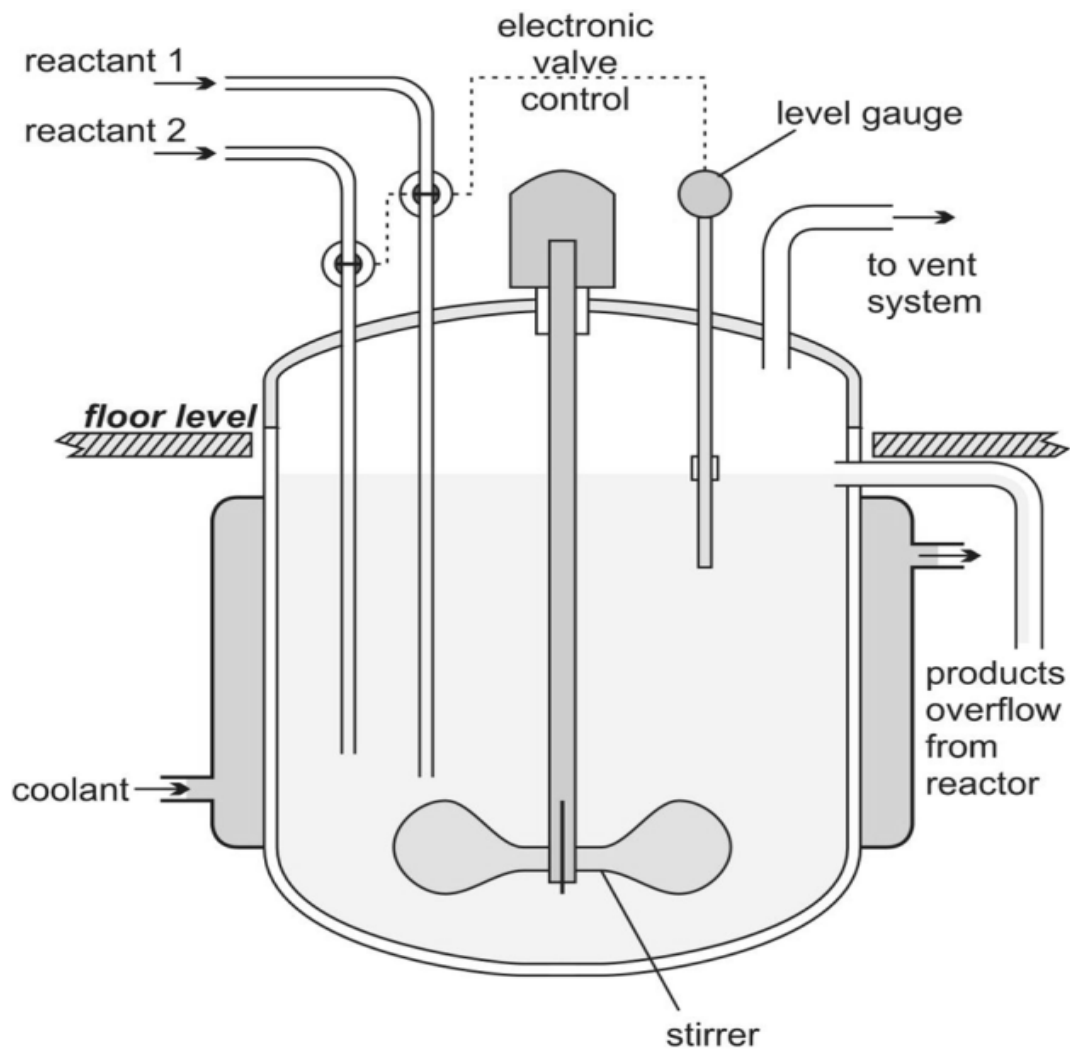
Chemical reactors are vessels which house the chemical reactions. Chemical reactors are designed to maximize net present value for the given reaction. It is ensured that the reaction proceeds with the highest efficiency towards the desired output product, producing the highest yield of product while requiring the least amount of money to purchase and operate. Energy changes can come in the form of heating or cooling, pumping to increase pressure, frictional pressure loss

Chemical reactor designs include continuous stirred tank reactors, batch stirred tank reactors, tubular reactors, and the packed bed reactors.

5.17.1 CSTR

In a CSTR, one or more fluid reagents are introduced into a tank reactor (typically) equipped with an impeller while the reactor effluent is removed. The impeller stirs the reagents to ensure proper mixing. Simply dividing the volume of the tank by the average volumetric flow rate through the tank gives the space time, or the average amount of time a discrete quantity of reagent spends inside the tank. At steady-state, the mass flow rate in must equal the mass flow rate out, otherwise the tank will overflow or go empty (transient state). While the reactor is in a transient state the model equation must be derived from the differential mass and energy balances. The reaction proceeds at the reaction rate associated with the final (output) concentration, since the concentration is assumed to be homogenous throughout the reactor. Often, it is economically

beneficial to operate several CSTRs in series. This allows, for example, the first CSTR to operate at a higher reagent concentration and therefore a higher reaction rate. In these cases, the sizes of the reactors may be varied in order to minimize the total capital investment required to implement the process.



Advantages of CSTR:

- ☐ It is possible to maintain this reactor at isothermal conditions for high heat of reaction.
- ☐ It is quite easy to maintain good temperature control with this reactor.
- ☐ Due to large volume, it provides a long residence time.
- ☐ It also has low cost of construction.

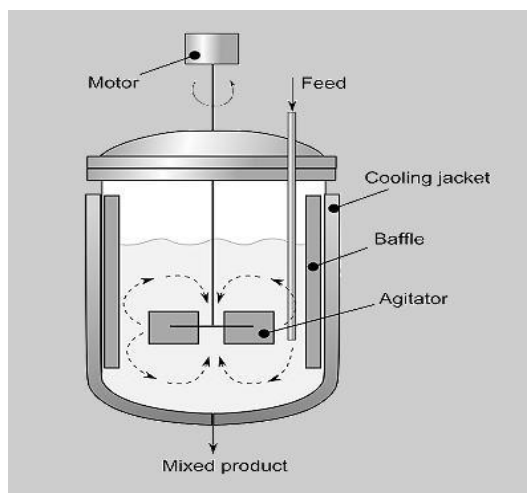
Disadvantages:

- ☐ It is not recommended for high pressure reactions because of cost consideration. For high pressure reactions it requires complex sealing arrangements for the agitator which increase the initial as well as maintenance cost.
- ☐ Conversion of these reactors is low due to this they are not preferred.
- ☐ These reactors are not suited for high heat effect since availability of both heat transfer coefficient and heat transfer per unit area is low.

Applications:

- ☐ These reactors are normally employed on commercial scale mainly for liquid phase reaction at low or medium pressure.
- ☐ It is commonly used in industrial processing of homogeneous reactions (only liquid phase) and usually used in series

5.17.2 BATCH REACTOR



In the batch reactor, the reactants are charged at the beginning into the reactor, it left to the react for certain period of time. During agitation no material is fed into the reactor. After certain time the product is withdrawn from the reactor. Actually batch reactor is used in the unsteady state condition as in this reactor composition is changes with time. The batch reactor actually consist of a cylindrical vessel have agitator for mixing the contents. External jacket is provided to heating or cooling the reactor contents.

Advantages :

- ☐ It is simple in construction
- ☐ It is so easy to operate
- ☐ Cost is relatively low
- ☐ It can give high amount of conversion

Disadvantages:

- ☐ It has high labour cost per unit volume of production.
- ☐ It requires considerable amount of time to empty, refill and clean out.
- ☐ Large scale production is difficult in this reactor.

Applications:

- ☐ Batch reactors are usually used in small scale industries.
- ☐ It is also used to produce many different product from small piece of equipments
- ☐ It is used for the manufacturing of expensive products like pharmaceuticals, dyes, dye intermediates etc.

5.18 Steam Boilers

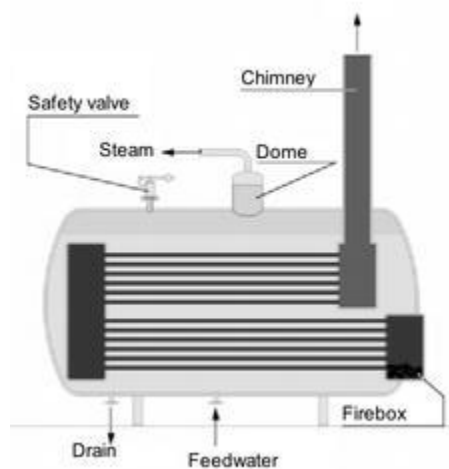
A boiler is a closed vessel in which water or other fluid is heated. The fluid does not necessarily boil. The heated or vaporized fluid exits the boiler for use in various processes or heating applications include water heating, central heating, boiler-based power generation, cooking, and sanitation.

Types of boilers:

Pot boiler, fire tube boiler, water tube boiler are some of the types of steam boilers.

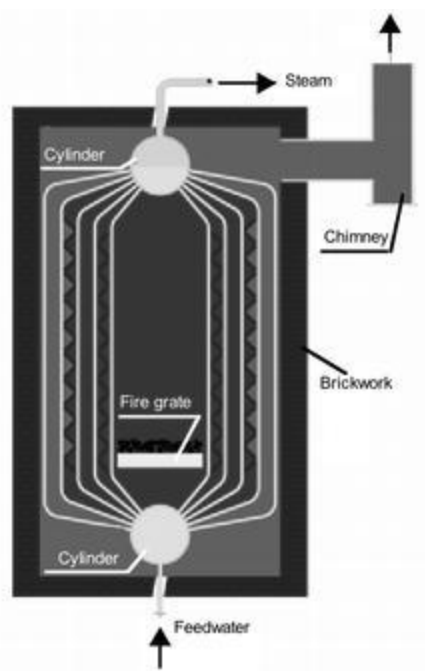
Pot boiler or Haycock boiler/Haystack boiler: a primitive "kettle" where a fire heats a partially filled water container from below. 18th century Haycock boilers generally produced and stored large volumes of very low-pressure steam, often hardly above that of the atmosphere. These could burn wood or most often, coal. Efficiency was very low.

Fire-tube boiler.



Here, water partially fills a boiler barrel with a small volume left above to accommodate the steam. This is the type of boiler used in nearly all steam locomotives. The heat source is inside a furnace or firebox that has to be kept permanently surrounded by the water in order to maintain the temperature of the heating surface below the boiling point. The furnace can be situated at one end of a fire-tube which lengthens the path of the hot gases, thus augmenting the heating surface which can be further increased by making the gases reverse direction through a second parallel tube or a bundle of multiple tubes alternatively the gases may be taken along the sides and then beneath the boiler through flues. Fire-tube boilers usually have a comparatively low rate of steam production, but high steam storage capacity. Fire-tube boilers mostly burn solid fuels, but are readily adaptable to those of the liquid or gas variety.

Water-tube boiler:



In this type, tubes filled with water are arranged inside a furnace in a number of possible configurations. Often the water tubes connect large drums, the lower ones containing water and the upper ones steam and water; in other cases, such as a mono-tube boiler, water is circulated by a pump through a succession of coils. This type generally gives high steam production rates, but less storage capacity than the above. Water tube boilers can be designed to exploit any heat source and are generally preferred in high-pressure applications since the high-pressure water/steam is contained within small diameter pipes which can withstand the pressure with a thinner wall.