Chapter 1

Chemical Process Projects

1.1 The Process Plant Design Problem

Chemical process projects involve the design, construction, commissioning, operation, and decommissioning of processes that involve physical, chemical, and biochemical change for the conversion of raw materials into useful chemical products on an industrial scale. Process designs are likely to differ significantly, depending on the type of product being manufactured. There are three broad classes of product:

1) *Commodity* or *bulk* chemicals are produced in large volumes and purchased on the basis of their chemical composition, purity, and price. Examples are sulfuric acid, ethylene, benzene, propane, and nitrogen.
2) *Fine* chemicals are also purchased on the basis of their chemical composition purity and price, but produced in small volumes. Examples are *n*-butyric acid (used in beverages, flavorings, and fragrances) and barium titanate (used for the manufacture of electronic capacitors).
3) *Specialty* or *effect* or *functional* chemicals are purchased on the basis of their effect or function, rather than their chemical composition. Examples are pharmaceuticals, pesticides, and flavorings.

In a chemical process, the transformation of raw materials into desired chemical products usually cannot be achieved in a single step. Instead, the overall transformation is broken down into a number of steps that provide intermediate transformations. These are carried out through reaction, separation, mixing, heating, cooling, pressure change, or particle size reduction or enlargement for solids. Once individual steps have been selected, they must be interconnected to carry out the overall transformation (Figure 1.1a). Thus, the *synthesis* of a chemical process involves two broad activities. First, individual transformation steps are selected. Second, these individual transformations are interconnected to form a complete process that achieves the required overall transformation. A *flowsheet* or *process flow diagram* (*PFD*) is a diagrammatic representation of the process steps with their interconnections.

Once the flowsheet structure has been defined, a *simulation* of the process can be carried out. A simulation is a mathematical model of the process that attempts to predict how the process would behave if it was constructed (Figure 1.1b). Material and energy balances can be formulated to give a better definition to the inner workings of the process and a more detailed process design can be developed. Having created a model of the process, the flowrates, compositions, temperatures, and pressures of the feeds can be assumed. The simulation model then predicts the flowrates, compositions, temperatures, pressures, and properties of the products. It also allows the individual items of equipment in the process to be sized and predicts, for example, how much raw material is being used or how much energy is being consumed. The performance of the design can then be evaluated.

Figure 1.2 shows an example of a very simple process flow diagram. The process flow diagram shows only the main items of equipment and the normal process flows. From this a *piping and instrumentation diagram* (*P&ID*) can be developed to include all of the equipment (including multiple items of equipment represented as single items in a process flow diagram, standby equipment, utility, and effluent treatment equipment directly linked to the process), the design of the control system, all piping connections and fittings (including those used for start-up, shut-down, maintenance, and abnormal operation), safety, relief and blowdown systems. Figure 1.3 shows the process flow diagram for the chemical reactor from Figure 1.2. Figure 1.4 shows the corresponding piping and instrumentation diagram (P&ID). When complete, the P&ID gives a complete graphical documentation of the process. Further details will be discussed in Chapters 15 to 17.

Process Plant Design, First Edition. Robin Smith.

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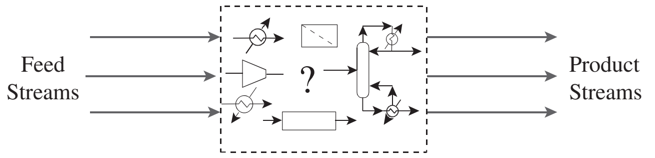
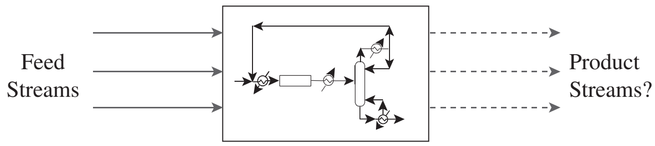


(a) Process design starts with the synthesis of a process to convert raw materials into desired products.



(b) Simulation predicts how a process would behave if it was constructed.

Figure 1.1

Synthesis is the creation of a process to transform feed streams into product streams. Simulation predicts how it would behave if it was constructed. Source: (Smith 2016), *Chemical Process Design and Integration*, 2nd Edition, John Wiley & Sons Ltd.

1.2 Continuous and Batch Processes

A fundamental decision that needs to be made early in a project is whether to adopt a continuous or batch design (Sharratt 1997). Small-scale processes, particularly those for specialty chemicals, pharmaceuticals, food, and beverages are often batch in nature. In principle, the process in Figure 1.2 could be continuous or batch in nature, depending on how it is operated. By contrast with the continuous process, in a batch process the main steps operate discontinuously. In contrast with a continuous process, a batch process does not deliver its product continuously but in discrete amounts. This means that heat, mass, temperature, compositions, and other properties vary with time. In practice, most batch processes are made up of a series of batch and *semi-continuous* steps. A semi-continuous step runs continuously with periodic start-ups and shut-downs.

Batch processes are often multiproduct in which a number of different products are manufactured in the same equipment. Multiproduct batch processes, with a number of different products manufactured in the same equipment, present even bigger challenges for design (Biegler, Grossman, and Westerberg 1997). Different products will demand different designs, different operating conditions, and, perhaps, different trajectories for the operating conditions through time. The design of equipment for multiproduct plants will thus require a compromise to be made across the requirements of a number of different products. The more flexible the equipment and the configuration of the equipment, the more it will be able to adapt to the optimum requirements of each product.

Batch processes:

- are economical for small volumes;
- are flexible in accommodating changes in product formulation;
- are flexible in changing the production rate by changing the number of batches made in any period of time;
- allow the use of standardized multipurpose equipment for the production of a variety of products from the same plant;
- are best if equipment needs regular cleaning because of fouling or needs regular sterilization;
- are amenable to direct scale-up from the laboratory, and
- allow product identification. Each batch of product can be clearly identified in terms of when it was manufactured, the feeds involved, and processing conditions. This is particularly important in industries such as pharmaceuticals and foodstuffs. If a problem arises with a particular batch, then all the products from that batch can be identified and withdrawn from the market. Otherwise, all the products available in the market would have to be withdrawn.

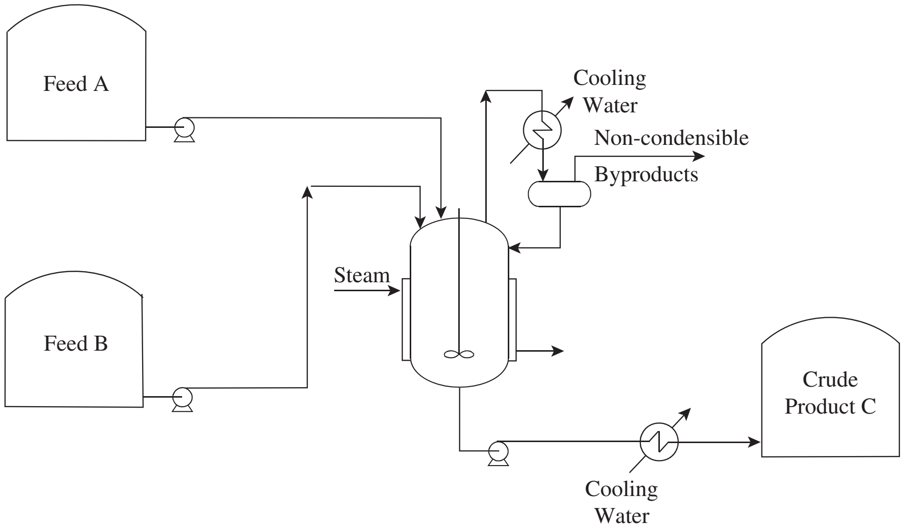


Figure 1.2

Process flow diagram for a simple process.

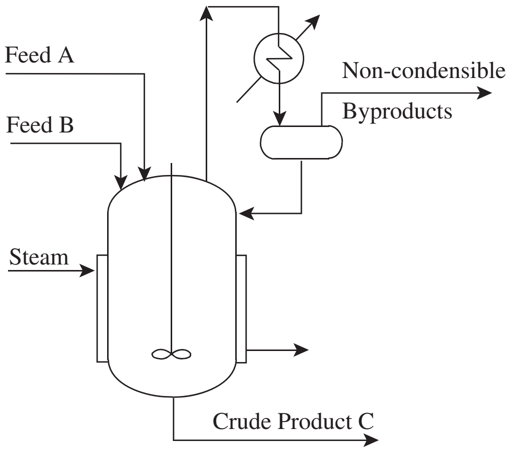


Figure 1.3

Process flow diagram representation for a reactor.

One of the major problems with batch processing is batch-to-batch conformity. Minor changes to the operation can mean slight changes in the product from batch to batch. Fine and specialty chemicals are usually manufactured in batch processes. However, these products often have very tight tolerances for impurities in the final product and demand batch-to-batch variation to be minimized.

1.3 New Design and Retrofit

There are two situations that can be encountered in process design:

1) *New build* or *greenfield* projects. New build projects require most of the deliverables to be generated from scratch.
2) *Retrofit* or *brownfield* projects. Retrofit projects might be an upgrade or production expansion of an existing facility or in extreme cases a complete rebuild of an existing facility.

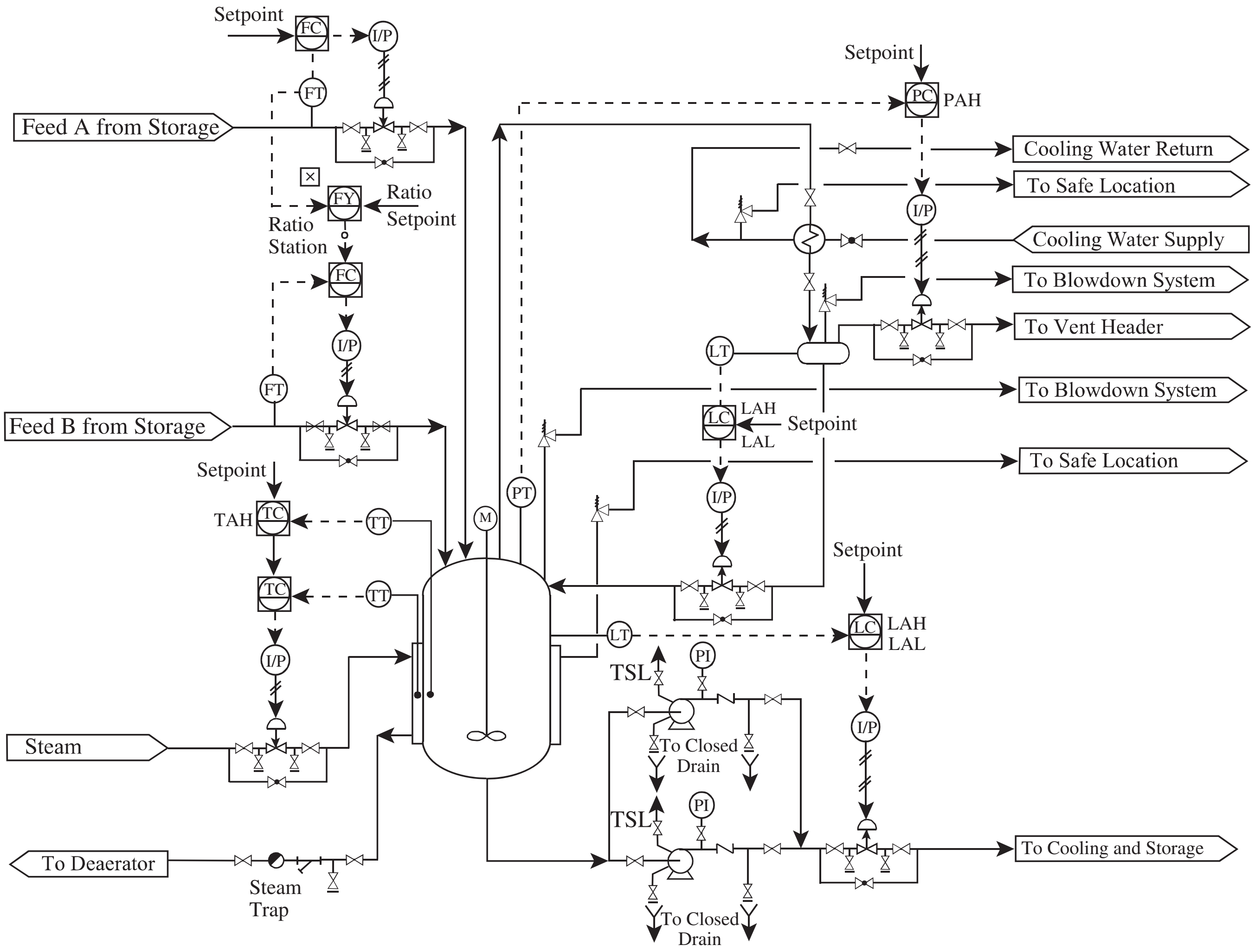


Figure 1.4

Piping and instrumentation diagram representation for the reactor from Figure 1.3.

New build (greenfield) projects and retrofit (brownfield) projects differ significantly. Retrofit (brownfield) projects require more effort at the outset to document what is currently installed and confirm the information used as the basis for the project. Retrofit projects are also highly constrained by the existing equipment. The objective is most often to maximize the use of existing equipment and minimize the introduction of new equipment. It is also necessary to minimize the downtime of the existing plant to implement the project.

1.4 Hazard Management in Process Plant Design

The major hazards of concern in process design are fire, explosion, and toxic release. To address these hazards, there is a hierarchy that should be followed for hazard management in process design, as illustrated in Figure 1.5:

a) *Inherent safety*. Make changes integral to the process to eliminate or reduce hazards at source, e.g. change from a process that uses a flammable solvent to a water-based process.

b) *Passive safety*. Incorporate design features that reduce the frequency or consequence of a hazard without the active functioning of a device, e.g. incorporate fire or blast protection walls.

c) *Active safety*. Requires active functioning of devices or personnel to mitigate hazardous conditions. This might require:

- process control systems to compensate for external disturbances and ensure safe operation within the normal operating envelope;
- safety instrumented systems (automated systems to prevent or mitigate hazardous events by taking the process from hazardous situations to a safe state);
- process alarms alerting process operators to abnormal operating situations, allowing a mitigating action to be taken by the operator;
- pressure relief using safety devices (e.g. pressure relief valve) to relieve any excessive pressure;
- active fire barriers requiring sprinkler and deluge systems to spray water onto a fire via a firewater distribution system. Human intervention is also active safety. However, human intervention is on the whole less reliable than process control and safety instrumented systems.

Figure 1.5

The hierarchy of hazard management. Source: (Smith 2016), *Chemical Process Design and Integration*, 2nd Edition, John Wiley & Sons Ltd.

d) *Procedural safety*. Using administrative controls and emergency response to prevent safety incidents or minimize the effects of an incident e.g. use of safety permits to control maintenance work.

All four levels in the hierarchy in Figure 1.5 can contribute to the overall safety of the process. However, inherent safety differs in that it seeks to eliminate or reduce potential hazards at source. It starts at the very beginning of the project and runs through all phases of the project execution.

Early in the project, formal managerial processes can be used for the identification of hazards, known as *hazard identification* (*HAZID*) studies. This is a structured brainstorming technique. The HAZID study should not only identify potential hazards, but consider the consequences of hazards and identify safeguards for the elimination or mitigation of hazards.

Later, when P&IDs have been developed, a *hazard and operability study* (*HAZOP*) should be carried out. This is a structured, qualitative procedure that identifies potential safety and environmental hazards and major operability problems, assesses consequences and generates recommendations for action, but does not attempt to modify the design. In the HAZOP, P&IDs are analyzed by dividing them into *nodes*, consisting of one or more processing units with a common goal, e.g. distillation (including the reboiler and condenser). Within each node, process parameters are investigated for *deviations* using *guide words*, e.g. higher temperature. The HAZOP identifies hazardous scenarios, but should not deal with their prevention or mitigation within the study. This should be done outside of the HAZOP.

After hazardous scenarios have been identified by the HAZOP, and outside of the HAZOP, various actions need to be taken to mitigate the hazardous scenarios identified. A *layer of protection analysis* (*LOPA*) should be carried out after the HAZOP study has identified hazardous scenarios. LOPA is used to determine which independent protection layers (e.g. safety instrumented systems) are needed to reduce the probability of the hazard occurring.

1.5 Project Phases

A typical project goes through a series of phases. The names given to the phases vary between different organizations. Typical phases are:

1) *Selection – concept development*. During the *Selection* phase of the project, a series of processing alternatives is developed and assessed for economic value, safety, environmental impact, sustainability, reliability, maintainability, availability, and risk. Process options are screened, such as batch versus continuous processing, different reaction and separation systems, different utility provisions, etc. If viable, the most promising process concepts progress forward to the next phase.

Selection includes:

- specification of feeds, products, and plant capacity;
- screening of existing process technologies;
- creation of process flow diagrams for the main process options;

- development of material and energy balances for the main process options;
- evaluation of plant location;
- hazard identification (HAZID);
- evaluation of environmental impact and sustainability;
- budgetary estimate of capital cost (see Chapter 2 for accuracy);
- estimation of operating costs and preliminary economic evaluation for main process options;
- identification of any new technology requirements;
- preparation of a statement of requirements.

2) *Definition – Front End Engineering Design*. The *Definition* phase is often referred to as *Front End Engineering Design* (*FEED*), *Front End Engineering* (*FEE*), or *Front End Loading* (*FEL*). The definition phase involves development of an engineering design and financial analysis from one or a small number of options created in the Selection Phase. The output is a design configuration, equipment details, and operating conditions needed to achieve the required economic criteria, safety standards, environmental performance, availability, and reliability. The design needs to be developed in enough detail and accuracy to provide the basis for the investment decision and, if approved, the commencement of the next phase. FEED studies can be carried out to different depths, depending on the requirements and time available. These can be defined as *light*, *normal*, or *extended*. The more work completed in the FEED phase, generally the more confidence there is in the next phase to be on budget and on schedule.

FEED includes:

- finalize process selection;
- finalize process and utility flow diagrams;
- finalize integrated material and energy balances;
- finalize environmental impact and sustainability assessment;
- preparation of equipment sizing and specification sheets for the major items of equipment;
- design of the control system;
- design of the relief, blowdown, and flare systems
- design of electrical systems;
- development of P&IDs;
- finalize necessary geotechnical surveys (ground surveys for civil engineering);
- create site and process layouts;
- HAZOP and LOPA studies;
- acquire the required permits and planning permissions;
- capital cost estimate and economic evaluation to a high enough accuracy for the decision on whether to sanction the investment (see Chapter 2 for accuracy);
- create project execution plan,
- finalize the basis of design.

3) *Execution – Engineering Procurement and Construction*. The *Execution* of the *Engineering Procurement and Construction* (*EPC*) phase is normally conducted for the production company by an Engineering Contractor. Different types of contract can be used between the EPC Contractor and the production company. The EPC contractor might be required to execute and deliver the project within an agreed time and budget, commonly known as a *Lump Sum Turn Key* (*LSTK*) Contract. Alternatively, a reimbursable arrangement might be used, where costs are dictated by the actual work carried out.

EPC includes:

- verify the basis of design;
- complete the detailed engineering design;
- finalize the control system design, including alarm and trip management;
- finalize the design of the electrical systems;
- create a 3-D model of the process;
- complete the piping design and create piping isometric drawings;
- finalize the details of the site and process layout;
- complete the civil and structural design;
- produce all construction documents and drawings;
- create a detailed bill of materials;
- produce an accurate capital cost estimate (see Chapter 2 for accuracy);
- create commissioning, operation, and maintenance manuals;
- project manage, and execute the design, procurement, and construction.

4) *Commissioning*. The *Commissioning* phase includes:

- test the integrity of all equipment and piping;
- test control systems and safety systems;
- start-up the process;
- operator training.

5) *Operation*. The *operation* phase includes:

- productive operation;
- operational optimization;
- asset management (maintenance and corrosion management).

6) *Decommissioning*. The *decommissioning* phase includes:

- safe disposal of residual process materials and chemicals;
- decontamination of equipment;
- dismantling and disposal of equipment and structures;
- site and ground remediation.

Decommissioning and end-of-life costs need to be considered early to ensure that excessive costs are not incurred at the end of the project.

1.6 Chemical Process Projects – Summary

A process design starts with the synthesis of a process flow diagram to transform raw materials into desired products. Once the process flow diagram has been fixed, piping and instrumentation diagrams (P&IDs) need to be developed. Small-scale processes, particularly those for specialty chemicals, pharmaceuticals, food, and beverage, are often batch in nature. Projects might be *new build* (*greenfield*) projects or *retrofit* (*brownfield*) projects. Early in the project, hazards should be identified by HAZID studies. Later, when the P&ID has been developed, a hazard and operability study (HAZOP) should be carried out followed by a layers of protection (LOPA) study.

A typical project goes through a series of phases:

- Selection – Concept Development;
- Definition – Front End Engineering Design (FEED);
- Execution – Engineering Procurement and Construction (EPC);
- Commissioning;
- Operation;
- Decommissioning.

References

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