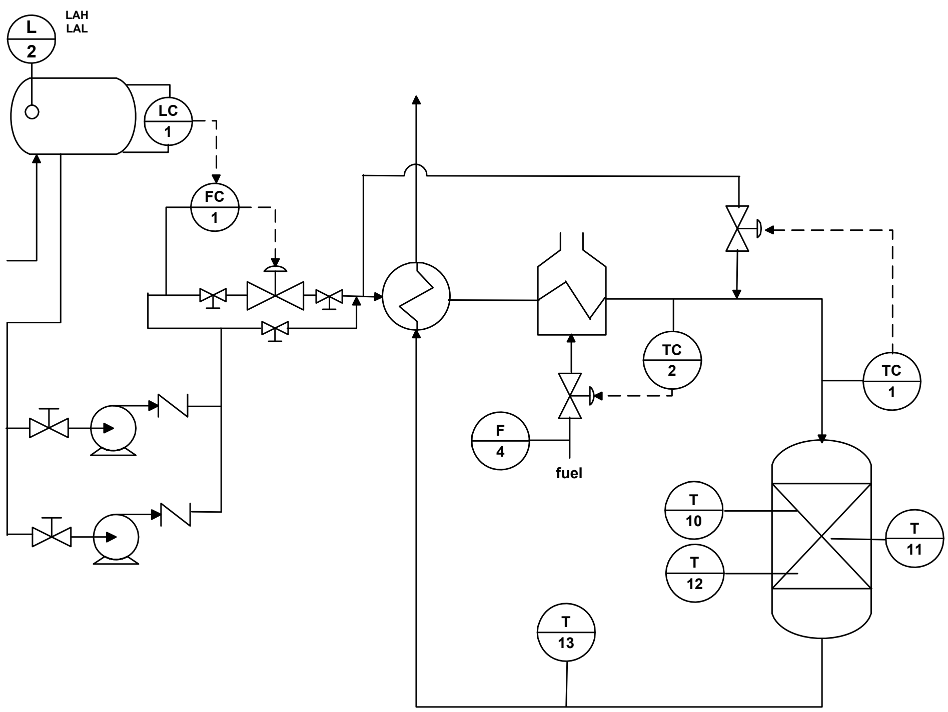
Operability in Process Design: Achieving Safe, Profitable, and Robust Process Operations

Chapter 3. Flexibility



Thomas Marlin

Flexibility release 1.5 on August 30, 2019

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Acknowledgements

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Disclaimer

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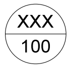
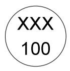
Symbols



CONTROL ROOM BOARD MOUNTED INSTRUMENT

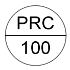


LOCAL BOARD MOUNTED INSTRUMENT

MEASURED VARIABLE:
L: LEVEL
P: PRESSURE
A: ANALYZER
F: FLOW
T: TEMPERATURE

FUNCTIONS:
I: INDICATOR
C: CONTROLLER
A: ALARM
(H =HIGH, L=LOW)

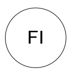
EXAMPLES:



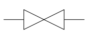
PRESSURE RECORDER CONTROLLER: I.D. NUMBER 100, MOUNTED IN CENTRAL CONTROL ROOM.

TAH

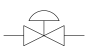
TEMPERATURE ALARM: ACTIVATED AT HIGH TEMPERATURE.



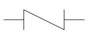
LOCAL FLOW INDICATOR



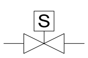
VALVE



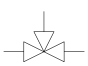
DIAPHRAGM VALVE: CONTROLLED BY AIR LINE



CHECK (ONE-WAY) VALVE



SOLENOID VALVE CONTROLLED BY ELECTRICAL SIGNAL

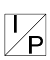


THREE-WAY VALVE

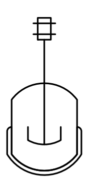
SPRING LOADED SAFETY VALVE

AIR LINE

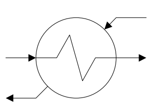
ELECTRICAL SIGNAL



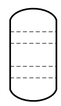
ELECTRICAL (CURRENT) TO PNEUMATIC SIGNAL CONVERTER



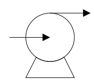
STIRRED TANK



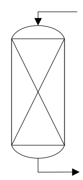
SHELL AND TUBE HEAT EXCHANGER



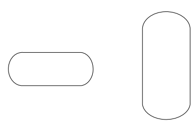
TRAYED COLUMN



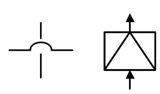
CENTRIFUGAL PUMP



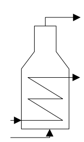
PACKED TOWER OR PROCESS VESSEL (SUCH AS A REACTOR).



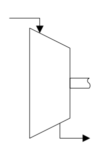
GENERIC TOWER OR PROCESS VESSEL (SUCH AS A REACTOR).



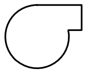
RUPTURE DISK, BURST DIAPHRAGM

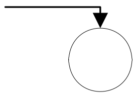


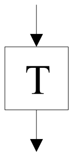
FIRED HEATER (FURNACE)



AXIAL COMPRESSOR

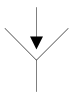

CENTRIFUGAL FAN

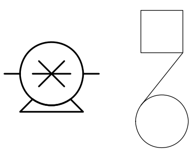

HEADER (STEAM OR CONDENSATE)

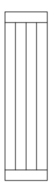


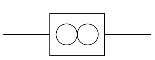
STEAM TRAP

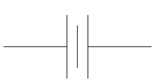
MOTOR

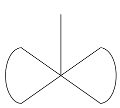

DRAIN TO SEWER

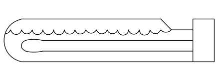

POSITIVE DISPLACEMENT PUMP

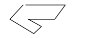

CONDENSER


TURBINE FLOW METER

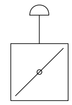

ORIFICE PLATE

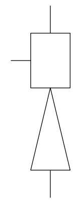

IMPELLER

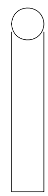

VAPORIZER OR REBOILER

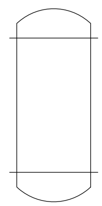

FILTER AND DRAIN

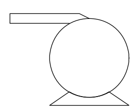

CYCLONE

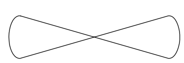

DAMPER OR BUTTERFLY VALVE

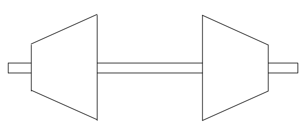

STEAM EJECTOR


FLARE STACK


SHELL AND TUBE HEAT EXCHANGER


FAN OR BLOWER


FAN


TURBINE USED TO PROVIDE WORK TO DRIVE COMPRESSOR

Nomenclature

A	Area, Subscript: Component symbol
A_H	Area for heat transfer
A_V	Cross sectional area
D	Pipe diameter
f	Friction factor
f( )	Functional relationship
F	Flow rate, volumetric
F_m	Flow rate, mass
ΔH_{vap}	Heat of vaporization
K	Velocity head factor
L	Length , level
NPSH	Net positive suction head
P	Pressure
Q	Heat transfer
t	Time
T	Temperature
U	Overall heat transfer coefficient
V	Volume
x	Volume fraction
z	Height

Greek symbols	
α	Relative volatility
β	Conversion from pressure units to head
Δ	Difference
ε	Error in flow measurement
ρ	Density

Chapter 3. Flexibility

3.0 To the Student

After graduation, you decide to purchase a new automobile with some of your enormous earnings. You understand the concept of an operating window, so you check the capacity of the design. You find that the model that you like has a large engine with good acceleration ability, powerful brakes, and a narrow turn radius. You conclude that the operating window for the model is excellent.

Then, you sit in the driver's seat. You notice that there are no pedals, neither accelerator nor brake. In addition, the steering wheel is missing. You recognize that having an adequate operating window is not enough; you need to be able to adjust key input variables – like wheel position, acceleration, and braking – to drive the automobile. Better not purchase that lemon! (A lemon is a defective product, especially an automobile; consider the Ford Pinto, Chevrolet Corvair, and many others.)

We will refer to the ability to adjust process operation as "flexibility". Flexibility provides the ability to move around in the operating window to achieve the desired operation in response to disturbances and set point changes. Naturally, both an adequate operating window and flexibility are required for a good design.

3.1 Introduction

We start with a single-point design case. Then, as we have learned in Chapter 2, we consider a range of operating conditions (that we need to achieve) to find the condition that places the greatest demand on the process capacity. The equipment is designed to function for this "limiting case".

Suppose that you are given the task of designing a condenser for a distillation tower with the limiting case conditions shown in Figure 3.1. You can perform design calculations to yield an area of about 28 m^3 (Ludwig, 1993). With this area (and a perfect model), the condenser will function well for this one operating point. However, what about other conditions, like a smaller flow of ammonia or a lower temperature for the cooling water? Clearly, we need the flexibility to adjust the operation; specifically, we need to change the rate of heat transfer. There are many possible designs that allow adjustments to the heat transfer rate; as an exercise, the reader should think of one or two design changes that can be introduced for this condenser. (We will consider heat exchangers, including condensers, later in this chapter.)

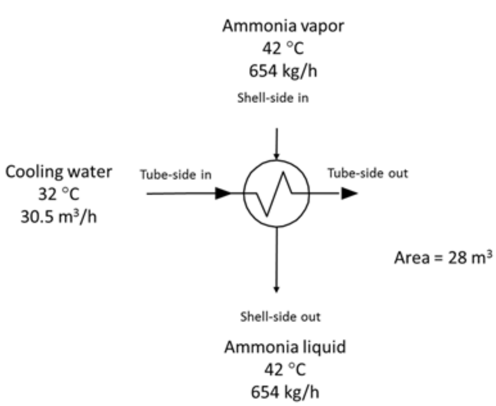


Figure 3.1. Condenser limiting design conditions with required exchanger area.

The astute reader will have noticed that moving in the operating window requires changing operating conditions, specifically adjusting selected manipulated variables. So, one could ask, "How does an engineer decide which variables are important (and are to be achieved) and which are not so important (and can be adjusted)?" These variables can be separated into two categories, controlled and manipulated variables, as explained in the following.

- **Controlled variables**: The important variables have a substantial effect on the key performance factors (KPIs) of the process, which include safety, reliability, product quality and profitability. Specific values for these important variables must be achieved.
- **Manipulated variables**: In contrast, the adjustable variables have much less effect on the KPIs of the process. Typical adjusted variables are steam flow, cooling water flow rate, fuel to a fired heater, and so forth. Note that these variables incur costs, so they are not "free", and the engineer should seek to reduce unnecessary use of these resources. However, their use in required and adjustments to their use, including prudent increases in their cost, is acceptable.

The design engineer can think of the regulation problem shown schematically in Figure 3.2. Certain controlled variables have been selected to be maintained at desired values, while disturbances occur to input variables. In order to maintain the controlled variables constant, manipulated variables must be adjusted. A useful way of thinking about this situation is that the variability in the disturbances is "moved" to variability in the (less important) manipulated variables, so that the (important) controlled variables can be maintained constant.

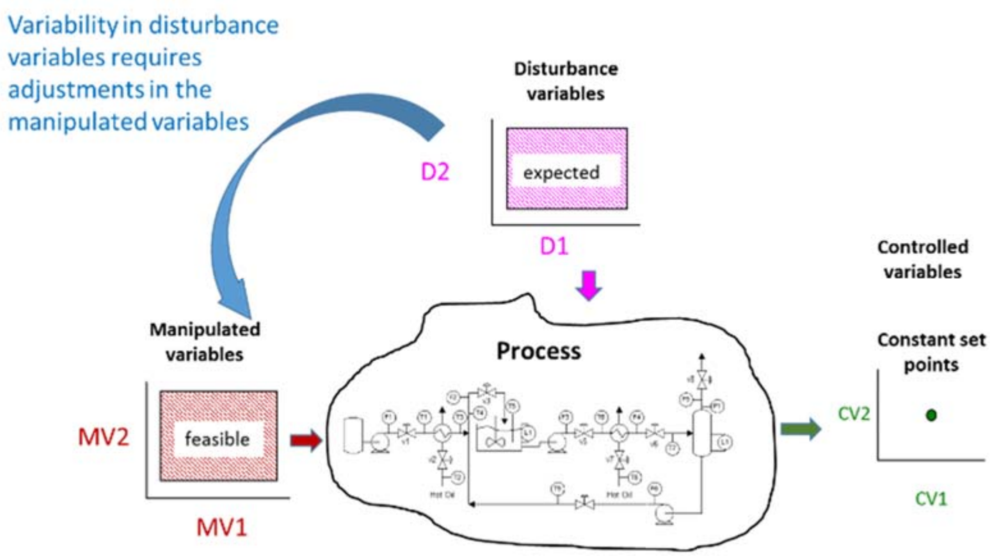


Figure 3.2. Relationship between variability in the disturbance and manipulated variables.

In Chapter 2, flexibility was provided by allowing the manipulated variables to be adjusted in the simulation model; these operating window studies demonstrate that the selected manipulated variables can provide adequate compensation, at least in the steady state. In a process design, flexibility is introduced by the design engineer by including equipment that enables the adjustment of the selected manipulated variables. The equipment can include valves, conveyor belts, motors, and turbines. Some of the adjustments can be automated using process control equipment and technology, while other adjustments require actions by personnel. In this chapter, many examples of design flexibility will be presented.

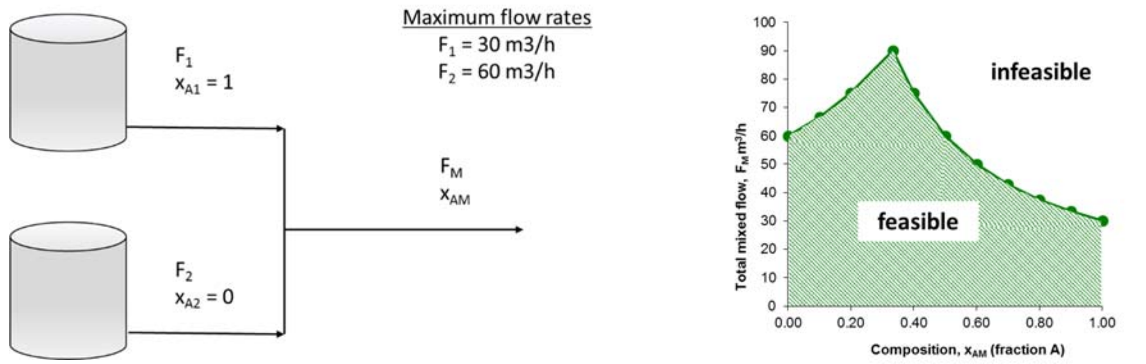


Figure 3.3. Process structure and operating window for Example 3.1.

Example 3.1. Blending We revisit the blending process analyzed in Example 2.1. The structure, data, and resulting operating window are shown in Figure 3.3. Determine the required equipment so that the flexibility can be achieved.

To achieve the entire operating window in Figure 3.4, each flow must be adjusted from zero to its maximum flow. This will require pumps to provide head for the flows and valves to adjust each flow rate; the process drawing includes constant speed centrifugal pumps. Since the flow rates are required to have very low values (including zero), recycle piping and valves are required so that a minimum flow can be maintained through each pump, even while the flows to the blending process are small or zero.

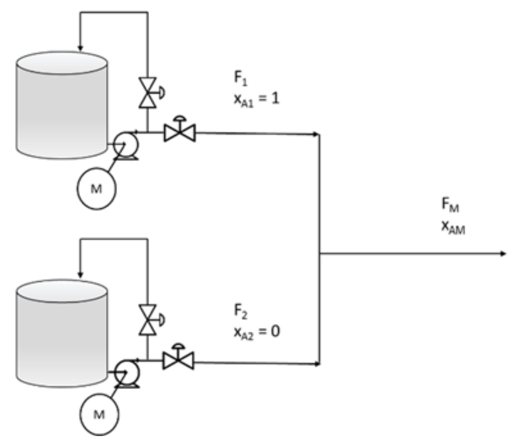


Figure 3.4. Flexibility required in Example 3.1.

This example is rather straightforward. Many readers would have designed an appropriate solution. However, we will see designs that are more challenging in later examples. The solutions to these examples will be discussed and documented in process sketches. To comprehend the solutions, the reader will need a rudimentary understanding of process control and standard symbols used in process drawings.

The remainder of the chapter is organized as explained in the following.

- Flexibility in material transport systems
- Flexibility in heat transfer systems
- Flexibility in inventory and production rate systems
- Flexibility in unit operations (boiler and steam system, distillation and refrigeration)

The designs presented in this chapter represent typical industrial flexibility and provide good learning examples. However, the designs do not comprehensively address all types of equipment or design issues related to flexibility; such an undertaking would overwhelm students and require an enormous volume of material. For the next stage in learning and engineering practice, the reader is advised to refer to Liptak (2003, 2005), which contains about 4500 pages on instrumentation and designs with control flexibility.

Also, the solutions in this chapter do not address important issues like safety that are covered in subsequent chapters.

3.2 Flexibility in material transport systems

Chemical processes involve the movement of raw materials, products, intermediate products (work in progress), and utilities like steam, fuel and cooling water. The rates of transport must be flexible to match product demand and respond to variability in material properties like pressure, enthalpy and composition. This section will address the movement of liquid, gas, and granular solids.

3.2.1 Principles of liquid flow in conduits

The system in Figure 3.5 involves fluid flow with constant inlet and outlet pressures and fixed resistance to flow. The total pressure drop is the sum of the individual pressure drops as shown in the following equation.

$$\Delta P = \rho g \Delta z = \sum \Delta P_{Hx} + \sum \Delta P_{vessel} + \sum \Delta P_{pipe} + \sum \Delta P_{fit} + \sum \Delta P_{valve} \tag{3.1}$$

with
ΔP_{Hx} = pressure drop due to heat exchanger
ΔP_{vessel} = pressure drop due to flow through vessel
ΔP_{pipe} = pressure drop due to flow through pipe
ΔP_{fit} = pressure drop due to fittings like expansion, contraction, elbow, etc.
ΔP_{valve} = pressure drop through partially opened valve

A flow that depends on gravity is the exception in process systems; we cannot build our process on the side of a hill, and gravity does not allow recycles or high pressures. However, there are some exceptions like liquid flow off trays in a distillation tower.

As shown in the figure, the system can have only one value for the flow rate, which is clearly not an acceptable design. To introduce flexibility, the engineer must add adjustable component(s), for example, the ability to adjust a resistance (e.g., a valve) or a pressure (e.g., pump or compressor).

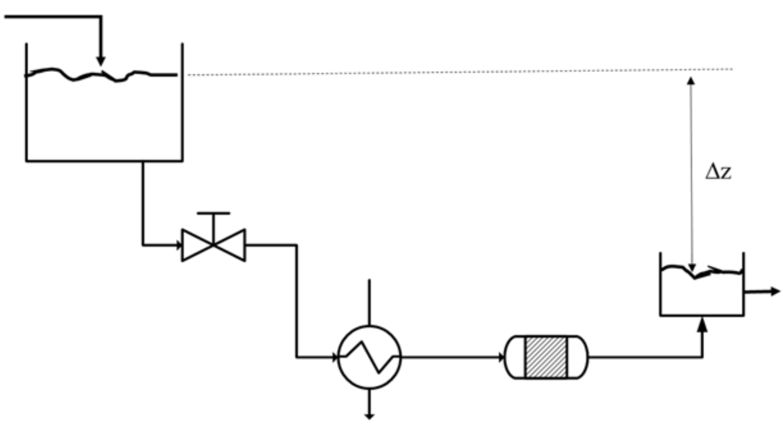


Figure 3.5. Sample liquid flow system.

Now, we will return to the liquid-flow system in Figure 3.5 with a constant pressure drop that observes the expression in equation (3.1). Each of the pressure drops depends on the flow through the specific element in the system according to the following expressions.

ΔP_{pipe} = pressure drop due to flow through pipe = $f\,(L/D)\,\rho F^2/2g$ (3.2)

ΔP_i = pressure drop for all other elements = $K_i\,\rho F^2/2g$ (3.3)

with
D = pipe diameter
f = friction factor
F = volumetric flow rate
K_i = velocity head factor for the specific element i
L = length of pipe
ρ = density

The friction factor depends on the Reynolds number, and correlations to evaluate the friction factor and velocity head factors are available in reference monographs and textbooks, e.g., Walas et.al. (1990). Substituting the individual expressions and rearranging to solve for the flow rate yields the following equation.

$$F = \sqrt{\frac{\Delta P}{[f(L/D) + \sum K_i]\rho/2g}} \tag{3.4}$$

Example 3.2 Flow system A process system involving liquid flow is shown in Figure 3.6. The pressures in the tanks are maintained constant by a flow of inert gas into/out of the tanks, as needed; this equipment is not shown in the figure. Is the flow flexible, that is, can various values of the flow be achieved by adjustments?

First, we note that this system does not require a pump, even though the exit elevation is above the initial elevation. This is not an unusual circumstance in a process design.

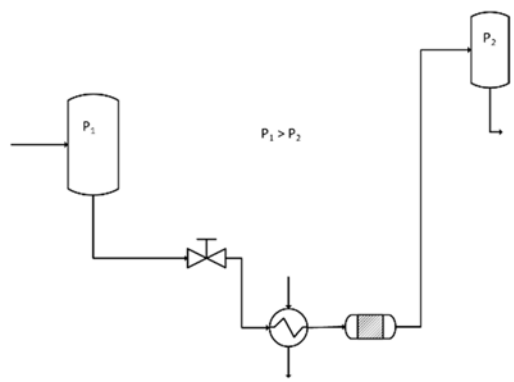
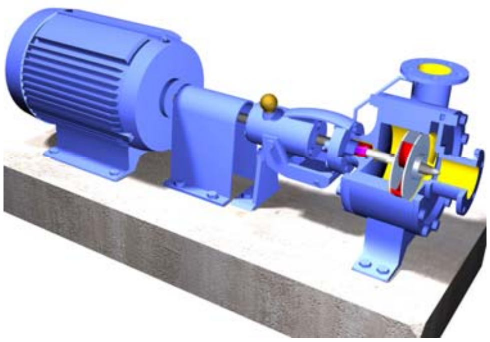


Figure 3.6 Flow system in Example 3.2.

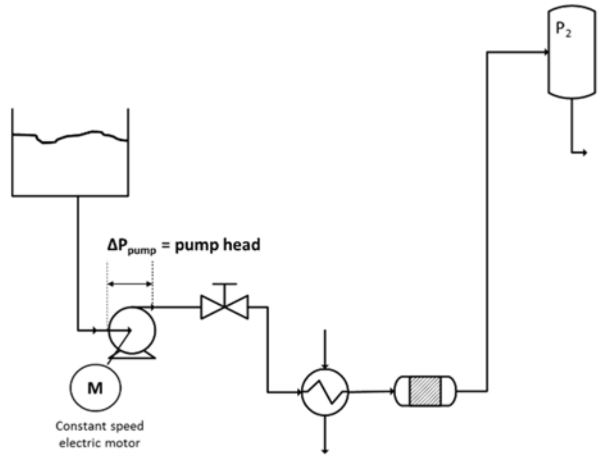
Next, we recognize that the relationship between the pressure drop and flow rate is given in equation (3.4). One resistance to flow, the valve, can be easily adjusted during plant operation. We can isolate this term in the defining equation as shown in the following.

$$F = \sqrt{\frac{\Delta P}{\left[f(L/D) + K_{valve} + \sum K_j\right]\rho/2g}} \tag{3.5}$$

In equation (3.5), the summation over “j” includes all elements except the valve. Clearly, as the valve resistance is changed by adjusting the valve opening, the flow is directly affected. For example, partially closing the valve increases its velocity head factor (K_{valve}), which results in decreased flow. Therefore, the design provides adequate flow flexibility.



a. Centrifugal pump cutaway with electric motor drive, Kaze (2010)



b. Liquid flow system with a centrifugal pump.

Figure 3.7. Flow system with centrifugal pump driven by a constant speed electric motor.

Example 3.3 Flow system In this example, we consider a liquid flow system with a constant speed centrifugal pump, as shown in Figure (3.7). The question is whether the system has adequate flow flexibility.

To determine the flexibility, we need to understand the behavior of the centrifugal pump (Fernandez, et.al, 2002; Moran, 2016). The basic principle of this type of pump is an increase in fluid velocity imparted by the impeller followed by a decrease in velocity in the volute (an empty volume inside the casing though which the liquid flows after departing the impeller. By Bernoulli's principle, as the velocity deceases, the pressure increases. Therefore, the pump outlet pressure is increased above the pump inlet pressure; the amount of the increase is termed the "pump head".

An important aspect of the centrifugal pump behavior is the slippage between the impeller and the liquid. The impeller can rotate at full speed with liquid in the casing but no net in or out flow through the pump. (Note that this operation can damage the pump, but it is possible for short time periods.) The resulting behavior of a pump is documented in a pump performance curve provided by a pump manufacturer; an example curve is given in Figure 3.8.

The steady-state flow rate for this system occurs when the pressure rise supplied by the pump equals the pressure losses due to flow and elevation changes. The pump pressure rise and "system losses" (due to the friction pressure losses and elevation changes) are given in Figure 3.9a. The steady-state flow rate can be determined graphically as the intersection of the pump head and system loss curves, as shown in Figure 3.9a with the valve fully opened. This solution represents the largest flow through the system. Now, we investigate the flow flexibility of the system. As shown in equation (3.5), the system curve is influenced by the valve resistance. Therefore, the intersection point defining the flow rate can be influenced by adjusting the system curve through the valve opening, as shown in Figure 3.9b. Therefore, this design has adequate flow flexibility.

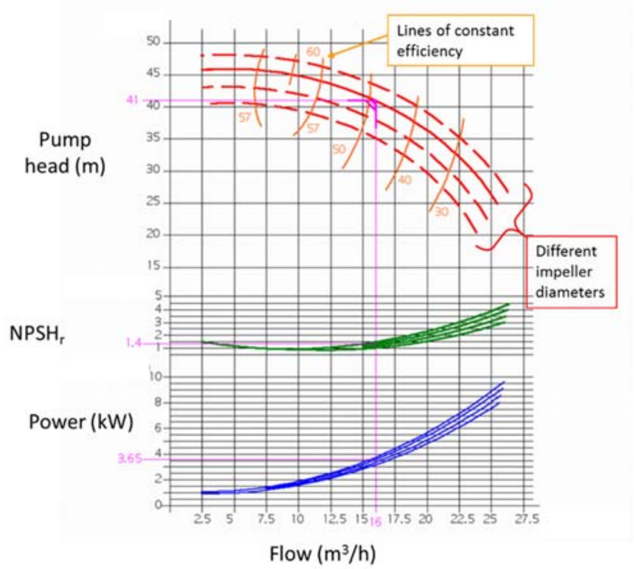
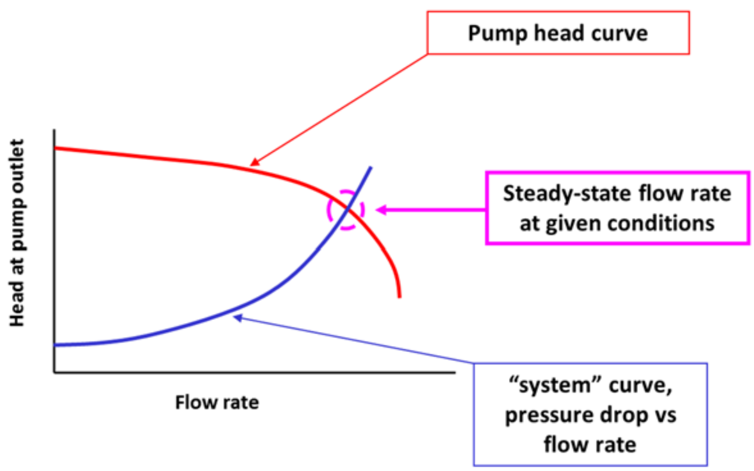
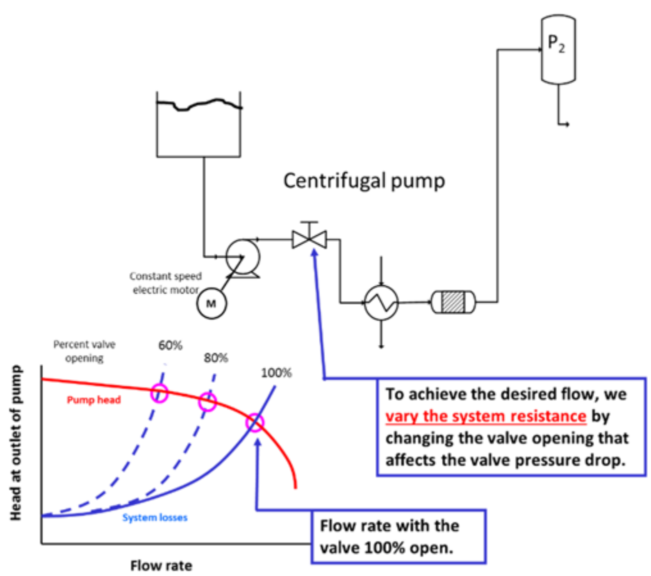


Figure 3.8. Typical pump performance curve including head, NPSH, and power, with the design point indicated. (Castelnuovo, 2005)

The figure includes results for four impeller diameters. Lines of constant efficiency are shown with values in percent.



a. Operating point with valve fully opened.



b. Effect of changing valve opening on flow rate

Figure 3.9. Liquid flow system with constant speed centrifugal pump.

Example 3.4 Variable speed motor This example addresses the same system as the previous example, except that a variable speed motor replaces the constant speed motor (DOE, 2004). Would this system have adequate flow flexibility?

A variable speed motor has the potential for reducing power consumption. The variable speed motor involves a higher capital cost, but it has a lower operating cost. Usually, an economic benefit can be achieved with large motors when the flow rate varies substantially from its design value. Naturally, this would only be acceptable if the design had good flow flexibility.

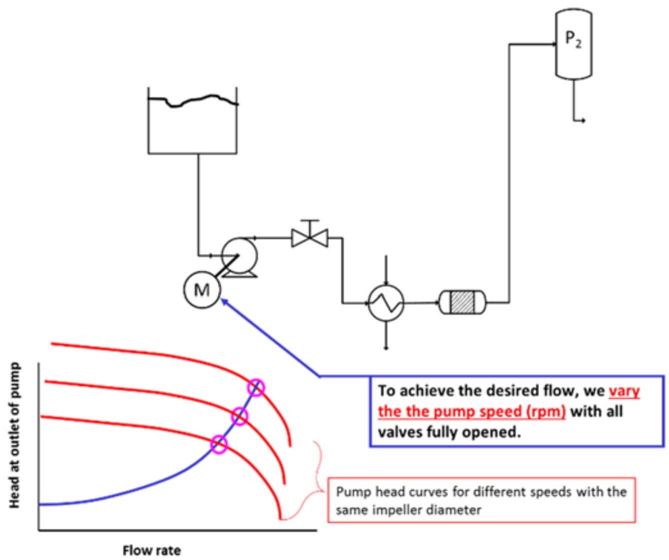
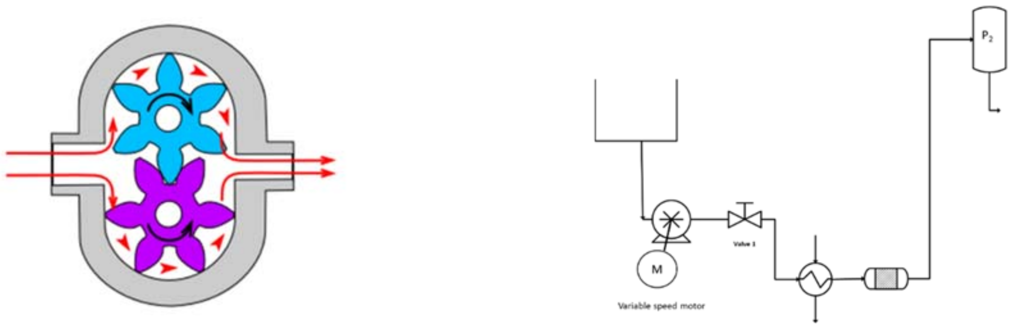


Figure 3.10. Liquid flow system with a variable speed centrifugal pump showing the effect of changing pump speed on flow rate with the valve constant at fully opened.

Varying the speed of the pump changes the pump head. With valves unchanged at fully opened, increasing (decreasing) the speed increases (decreases) the pressure at the outlet of the pump and increases (decreases) the flow rate. The pump performance curve showing the effect of variable speed is given in Figure 3.10; a steam turbine could provide the variable speed drive in place of the electric motor. Therefore, this design has adequate flow flexibility.

Example 3.5 PD pump This example addresses the same system as the previous example, except that a positive displacement (PD) pump replaces the centrifugal pump. Would this system have adequate flow flexibility?

A positive displacement pump captures a volume of incompressible liquid and transports it through the pump from the inlet to the outlet. Many types of positive displacement pumps are available, including both reciprocating and rotary principles; a sketch of a rotary gear positive displacement pump is shown in Figure 3.11a. Positive displacement pumps are favored for lower flow rates with higher pump heads and fluids with high viscosity; also, positive displacement pumps can provide accurate metering of flow.



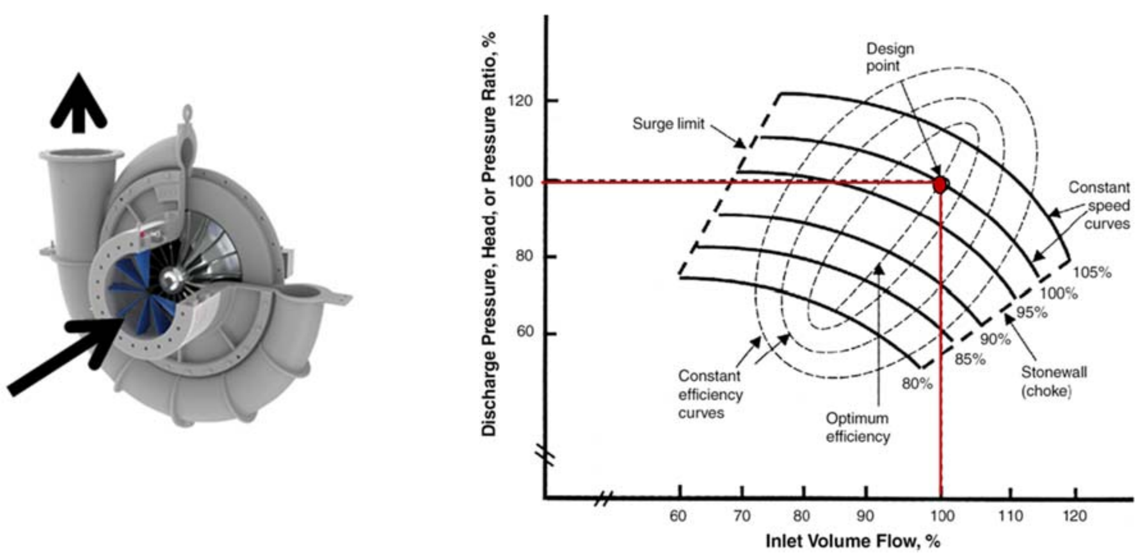
a. Gear pump, Duk (2050) b. PD pump with variable speed motor

Figure 3.11. Flow system with positive displacement pump

Unlike a centrifugal pump, the positive displacement pump involves very little “slippage” between the moving parts and the pump casing. One strong effect on the flow rate is the speed of movement, either the rotary speed (as in Figure 3.11) or the cycling speed of a piston. The other strong effect is the length of the piston movement per cycle. For the rotary gear pump, the flow rate can be changed by adjusting the speed of the driver, as shown in Figure 3.11b. Therefore, this flow system has adequate flow flexibility.

3.2.2 Gas flow in conduits

The basic principles for gases are similar to those for fluids. In industrial flow systems, a higher source pressure is required. A flow system like the one shown in Figure 3.6 provides adequate flow flexibility when the pressure difference is high enough to overcome the flow resistances in the process. When the process pressure difference does not provide sufficient driving force, a compressor is required. Many types of compressors are available; this section will address rotary compressors commonly used in process plants.



a. Centrifugal compressor, Howitworks (2015)

b. Typical compressor performance curves with normalized values on axes, Smith (2013)

Figure 3.12 Variable speed centrifugal compressor

Compressors provide increased pressure at the expense of work provided by an electric motor or steam turbine. A figure showing a centrifugal compressor is given in Figure 3.12a, and the operating window for a compressor is shown in Figure 3.12b. As the flow rate increases, the system approaches a “stonewall” beyond which increases are not achievable. As the flow decreases, the system reaches a surge point; surge involves rapid reverses in the flow direction that can quickly damage (even destroy) the compressor (Staroselky and Ladin, 1979). Therefore, operation to the left of the surge line is avoided at all cost.

Example 3.6 Centrifugal compressor A flow system including a rotary compressor is given in Figure 3.13. Does this have adequate pressure and flow flexibility?

We observe that the flow rate is determined by a valve opening in the process before the compressor that is manipulated by flow controller FC-1. This represents a typical situation were upstream processes determine the flow to the compressor. The compressor must raise the pressure of all of the inlet gas to the outlet pressure, which is determined by a downstream process. The process has flexibility in the driver speed, but it will not automatically achieve the desired process pressure or to ensure that the flow through the compressor is large enough to prevent surge.

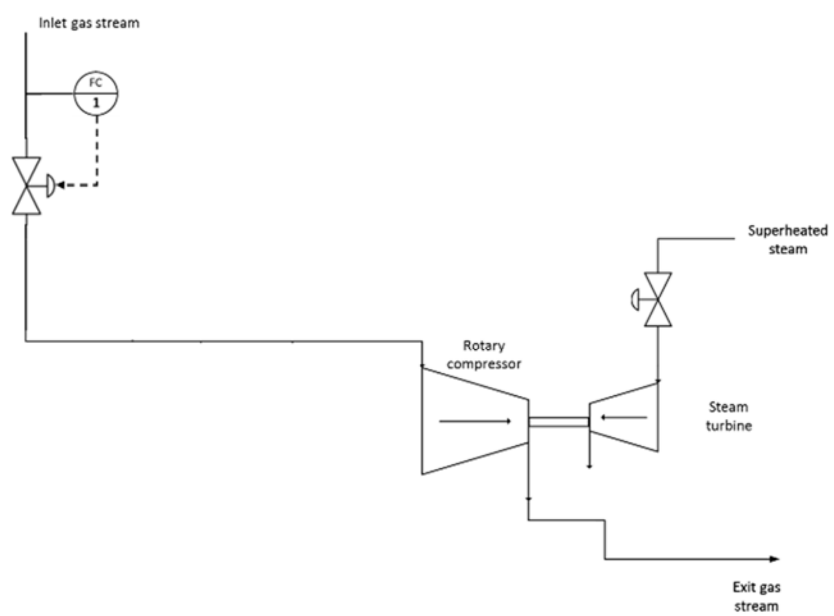


Figure 3.13 Basic compressor flow system

The design in Figure 3.14 achieves typical process operability objectives. The pressure controller adjusts the work by the turbine on the compressor via a cascade controller adjusting the speed controller set point. This ensures that the process pressure is maintained at a desired value. The flow through the compressor is regulated at or above a minimum limit by the action of the flow controller FC-2. This prevents the compressor from operating left of the surge line in Figure 3.12b, which would lead to equipment damage. Further details on anti-surge control is available from White (1972) and Staroselsky and Ladin (1979). We conclude that the design in Figure 3.3 has adequate flexibility.

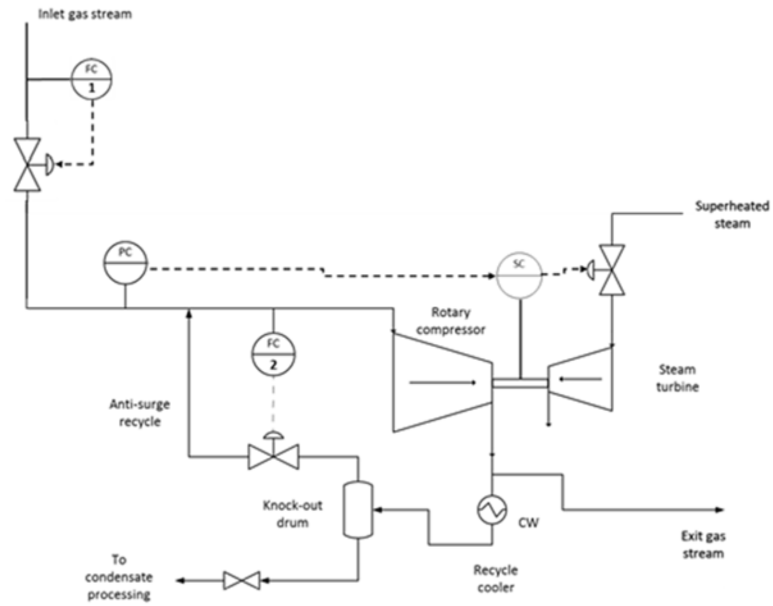


Figure 3.14. Compressor design with flexibility

Example 3.7 Guide vanes Fans are often employed to provide air for combustion systems. How is the air flow regulated in this type of compressor?

The term fan is applied to a compressor that moves large volumes of gas at low head, as required when providing air to a burner in a boiler or fired heater. A variable speed drive can be used for the control of a fan and would provide the highest efficiency at higher capital cost. However, the power is often provided by a lower-cost, constant speed motor. Flow flexibility could be provided using a valve in the duct, which would significantly reduce the efficiency due to friction losses. A common method for regulating flow with constant speed fans is guide vanes that are designed and manufactured by the fan supplier. The vanes change the direction of air flow entering the impeller, thereby influencing the flow rate (AirBestPractices, 2019). The design in Figure 3.15 has adequate flow flexibility.

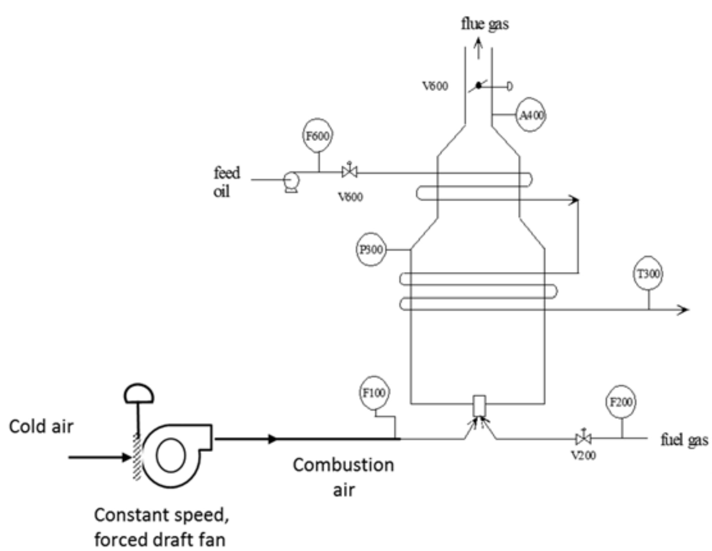


Figure 3.15. Constant speed fan with inlet guide vanes that can be adjusted to achieve the desire air flow rate

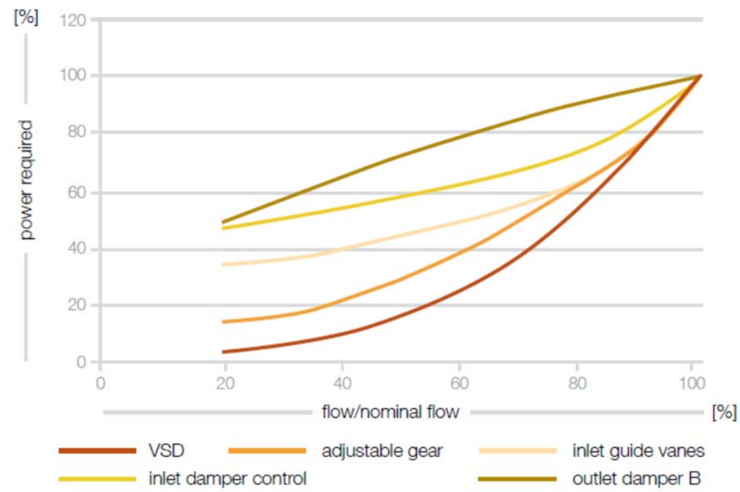


Figure 3.16. Efficiency for various flexibility methods for a fan. Westinghouse Bulletin B-851

Several methods for flow flexibility have been introduced; which is best? The selection depends on the economics, but the relative energy efficiencies are known, as shown in Figure 3.16. Clearly, the variable speed driver (either motor or steam turbine) is most efficient, and either inlet or outlet dampers (valves) being least efficient. Since the variable-speed drive (VSD) is typically more expensive, the engineer must performance an economic analysis to select the best choice. However, flexibility of some type is essential for a successful design.

Example 3.8 Reciprocating compressor Positive displacement compressors are favored for high-pressure systems. How is flow flexibility provided for reciprocating compressors?

A reciprocating compressor involves a piston that compresses the inlet gas and exhausts it at a higher pressure. Flow flexibility can be provided with a recycle or "spillback" system as shown in Figure 3.17. This design is inefficient, so it is often combined with an "unloading" control that adjusts the volume of gas per piston cycle.

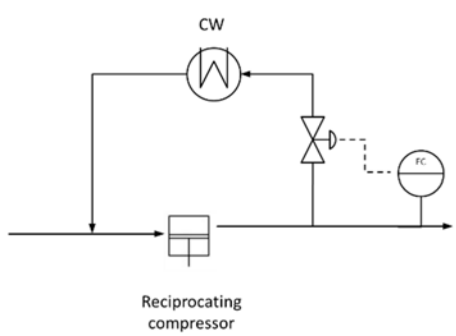


Figure 3.17. Reciprocating compressor with spillback for flow control

3.2.3 Solids transport

The movement of solid materials involves a diverse array of equipment. Here, the presentation is limited to granular solids, which are common in the process industries. Naturally, conveyor belts provide one method for transporting solids, and the rate of transport can be adjusted by changing the speed of the belt. A few other common methods for solids transport are shown in Figure 3.18. Flow flexibility is provided by changing the rotary valve rotation speed, the screw rotation speed, and the bucket travel speed, respectively.

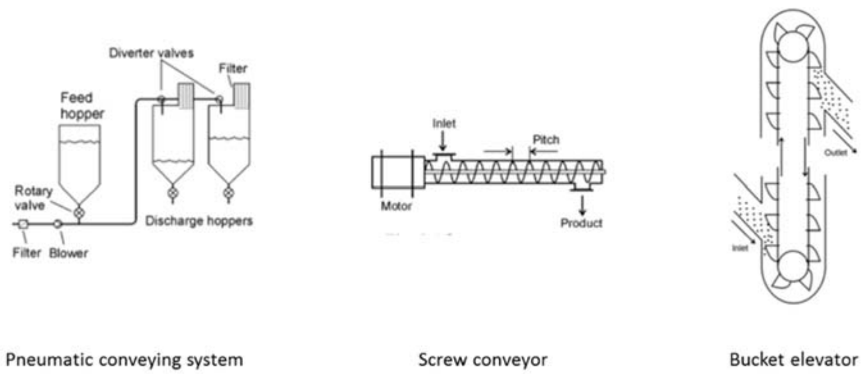


Figure 3.18. Solids transportation systems, from Holdich (2002) with permission

3.3 Flexibility in Heat Transfer

Most chemical systems function best in a narrow range of temperatures; examples include chemical reactors, mass transfer processes, and biological systems. The proper temperature of a process environment is not a fundamental objective, but the proper temperature environment contributes to safety, reliability and high product quality. Therefore, heating and cooling at well-regulated rates are essential for achieving good process performance.

3.3.1 Heat exchangers

We will begin with the most common heat exchanger, the shell and tube exchanger in Figure 3.19. Typically, we desire to achieve a specific value for the temperature of one of the exiting streams. The system in Figure 3.19 does not have flexibility; how can an engineer add flexibility to control one outlet temperature?

Heat transfer in an exchanger is determined using an equation of the following form.

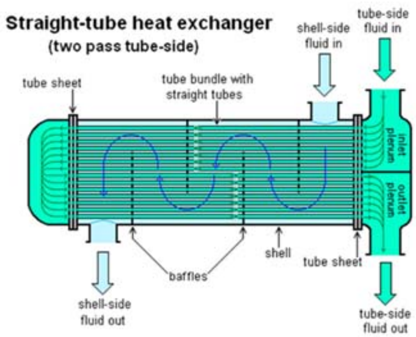
$$Q = U\ A\ \Delta T \tag{3.6}$$

with

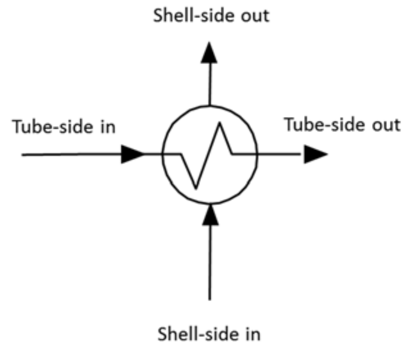
Q = the rate of heat transfer
U = the overall heat transfer coefficient
A = the heat transfer area
ΔT = the temperature difference (modified for specific flow structure, e.g., log mean)

Adding flexibility to the heat transfer process involves introducing ways to adjust one or more of the terms on the right-hand side of equation (3.6). The reader might be surprised to learn that standard industrial designs exist that influence the heat transfer rate by changing every term in equation (3.6), i.e., the heat transfer coefficients, the temperature difference, and even the area!

Example 3.9 Shell and tube Add flexibility to the shell and tube heat exchanger in Figure 3.19 so that the cold outlet temperature can be controlled.



a. Exchanger schematic, Padleckas (2006)



b. Piping and instrumentation symbol

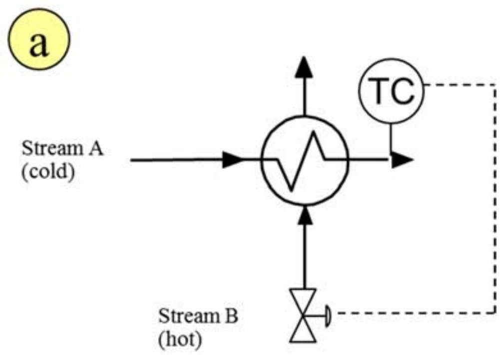
Figure 3.19 Shell and tube heat exchanger

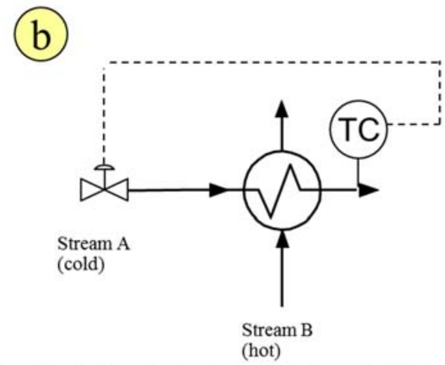
Several solutions are presented in Figure 3.20a to c and discussed in the following.

- In Figure 3.20a, the stream flow rate not involving the controlled temperature is manipulated. Changing the flow rate affects the heat transfer coefficient and the average temperature difference. This is an appropriate design when the total flow rate of the manipulated stream can be changed, which is acceptable for utilities like steam, cooling water and air.
- In Figure 3.20b, the stream flow rate involving the controlled temperature is manipulated. Normally, we desire to control both the production rate and stream temperature. Therefore, this is not generally an acceptable design because the production rate must be adjusted to achieve an intermediate product stream temperature.
- In Figure 3.20c, the total flow rates of both streams are not affected by the temperature control. One stream is split between a by-pass and a stream passing through the exchanger. The smaller flow rate through the exchanger results in a smaller heat transfer coefficient and smaller temperature difference. With this design, both streams can be process material (or a utility) because neither total flow rate is influenced. The better choice for the by-pass side is the temperature being controlled, because the dynamics of mixing is very fast, so that the temperature can be maintained close to its set point with fast feedback action.

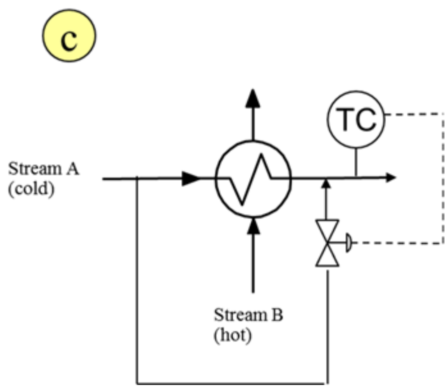
Example 3.10 Enhanced by-pass control The design in Figure 3.20c has a deficiency. Zero by-pass flow can be achieved by closing the control valve, but total by-pass, with no flow through the exchanger, cannot be achieved. Improve the design.

The design in Figure 3.21 using two valves can extend the range of manipulation to include both full by-pass and zero by-pass. The same controller output signal is sent to both control valves, with v100 being fail closed and v200 being fail open. The effect of the controller output on the valve openings is shown in the figure. Thus, the total flow rate can be unchanged while the flow through the exchanger can be adjusted. This control design provides adequate flexibility with a large range of operation.





It is not typical to adjust a stream flow to control its temperature; if the temperature is important, likely the flow rate is also important..



Freedom to adjust total flow rates

	Stream A	Stream B
a.	Constant	Adjustable
b.	Adjustable	Constant
c.	Constant	Constant

Figure 3.20. Temperature control of the exit from a heat exchanger.

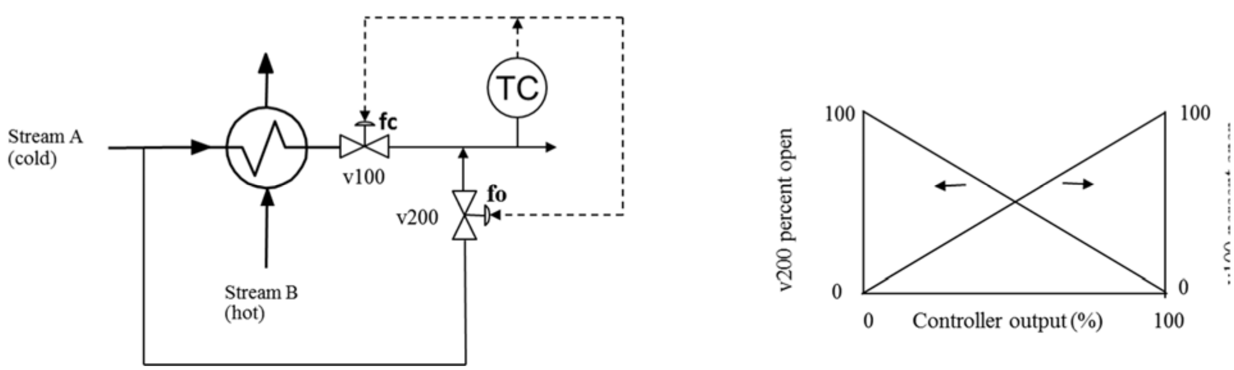
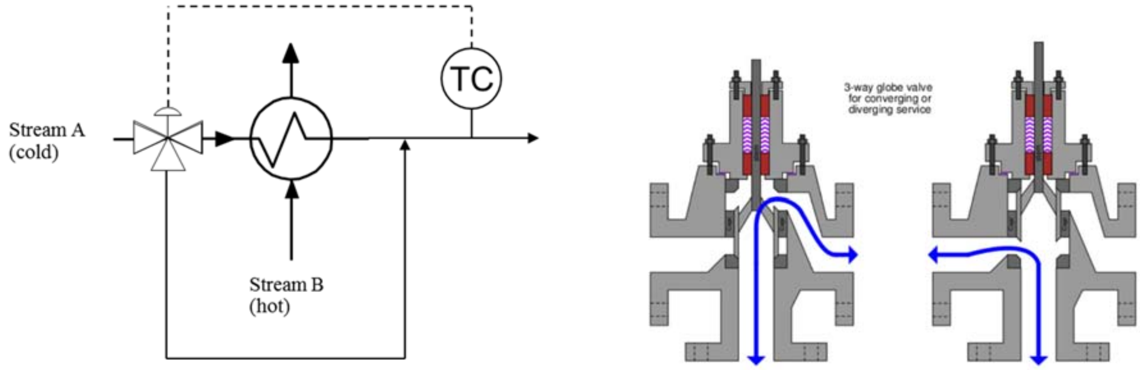


Figure 3.21 By-pass control using two valves

Example 3.11 Three-way valve All advantages of the previous example can be achieved by replacing two valves with one three-way valve.

The design is shown in Figure 3.22a with the split of the total flow achieved by the three-way valve, and a schematic of a three-way valve is given in Figure 3.22b. Thus, the total flow rate can be unchanged while the flow through the exchanger can be adjusted. This control design provides adequate flexibility with a large range of operation.



a. Control design with three-way valve b. Schematic of three-way valves, Kuphaldt (2019)

Figure 3.22 By-pass control using a three-way valve

Heat exchange using refrigerant is required to achieve temperatures below that possible with cooling water from a cooling tower. Liquid refrigerant is provided by a utility process in the plant, and the liquid refrigerant is vaporized in the exchanger due the heat transfer. The basic design in Figure 3.23 has no flexibility, which is not acceptable.

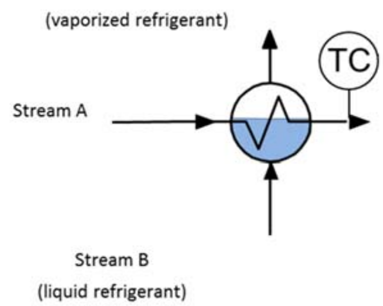


Figure 3.23 Heat exchanger using refrigerant cooling.

Example 3.12 Vaporizing heat exchanger Add flexibility to the design in Figure 3.23.

We refer back to equation (3.6) and note that adjusting the area would provide flexibility, but how do we influence the area once the heat exchanger has been fabricated and installed? A very direct method is shown in Figure 3.24a. In this design, the temperature controller adjusts the flow rate of liquid to the exchanger. The heat transfer and rate of vaporization of the liquid refrigerant depends on the liquid level; as the level increases (decreases), the heat transfer and the rate of vaporization increases (decreases). The reader likely remembers that many levels in the process industries are unstable and require control, so we should check the stability of the level in the exchanger. We formulate the material balance of liquid in the exchanger in the following.

$$\frac{d(\rho V)}{dt} = (F_m)_{in} - (F_m)_{out} \tag{3.7}$$

with
ρ = liquid density
V = volume of liquid in the exchanger
F_m = mass flow rate of refrigerant

We note the volume is related to the level; for a cylindrical vessel, the volume and area are related by

$$V = A_V * L \tag{3.8}$$

with
A_V = the (constant) cross sectional area of the vessel
L = liquid level in the heat exchanger

(This stability analysis will be valid for other geometries.) In addition, the flow of vaporized refrigerant depends on the rate of heat transfer, which in turn depends on the area for heat transfer, which depends on the level of the liquid refrigerant.

$$(F_m)_{out} = \frac{Q}{\Delta H_{vap}} = \frac{UA_H(\Delta T)}{\Delta H_{vap}} = \frac{U(\Delta T)}{\Delta H_{vap}} f(L) \tag{3.9}$$

with

ΔH_{vap} = heat of vaporization of the refrigerant

A_H = area for heat transfer

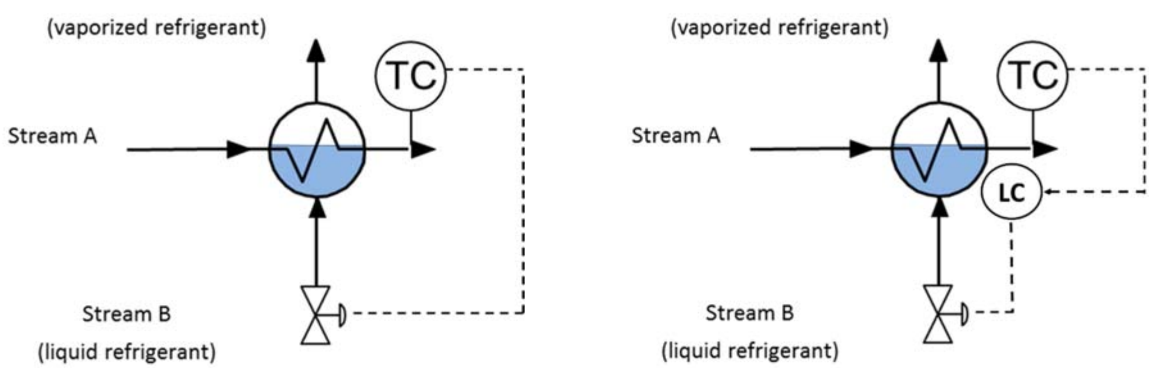
$f(L)$ = a functional relationship between the heat transfer area and the liquid level, which is complex and depends on the heat exchanger design, e.g., horizontal or vertical. The relation involves a monotonic relationship with a positive sign, i.e., as the level increases, the heat transfer area increases.

The results from equations (3.8) and (3.9) can be substituted into equation (3.7) to yield the following.

$$\rho A_V \frac{dL}{dt} = (F_m)_{in} - \frac{U(\Delta T)}{\Delta H_{vap}} f(L) \tag{3.10}$$

We observe that the level dynamics are first order. The flow in depends on the valve opening and not on the liquid level. As the level increases, the rate of change of the level decreases. Therefore, the level is self-regulating (Marlin, 2000), and the level process is stable without feedback control. We conclude that the design in Figure 3.24a has adequate flexibility and acceptable dynamic behavior.

The vaporizer refrigerant returns to a compressor in the refrigeration process that supplies the cooling. Naturally, the overhead stream must never contain liquid to prevent damaging the compressor. To prevent liquid carryover, the design can be modified as shown in Figure 3.24b, in which the temperature controller serves as a primary in a cascade design that adjusts the set point of the secondary level controller. In this cascade design, the level is controlled, and it should not exceed its upper limit. A second advantage for this design is the measurement and display of the liquid level, which can be used to determine the capacity utilization of the heat exchanger, because when the level is near its maximum, the heat transfer rate is near its maximum.



a. Flexibility by changing the area, single feedback controller

b. Flexibility by changing the area, cascade feedback controllers.

Figure 3.24. Heat exchanger using refrigeration with flexibility

As alternative approach for controlling refrigeration exchangers is also based on the principles in Equation (3.6). In this design, the area is constant at its maximum value by controlling the liquid level at its maximum in the exchanger, and the temperature difference is adjusted for flexibility. The refrigerant temperature depends on the pressure because the refrigerant is boiling. The control design in Figure 3.25 regulates the temperature by adjusting the valve on the vapor exit pipe. As the valve opening is increased (decreased), the pressure of the boiling refrigerant decreases (increases), and the temperature of the refrigerant decreases (increases). This approach gives a faster response than changing the area (liquid level). However, the additional pressure drop in the refrigeration circuit reduces efficiency and increases power consumption.

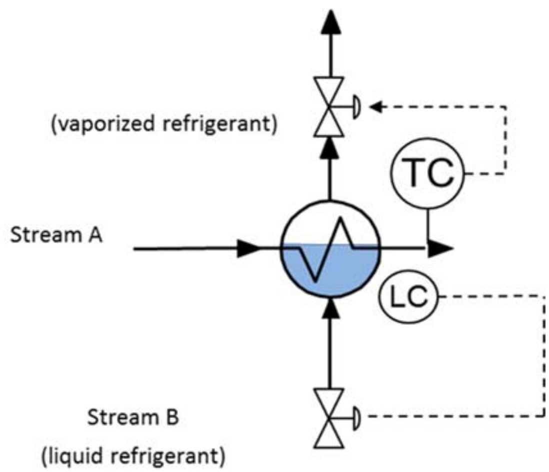
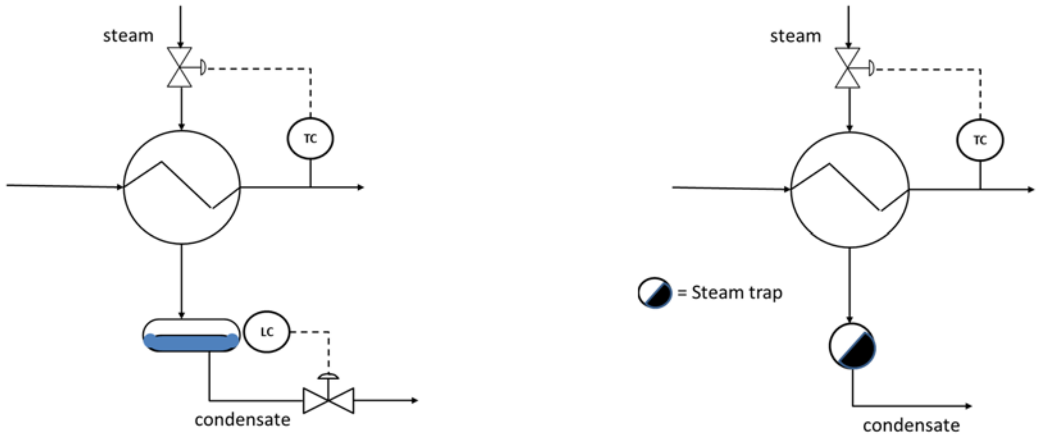


Figure 3.25 Heat exchanger with refrigeration with flexibility by adjusting boiling pressure.

Another common heat exchanger medium is steam for heating. Most of the heat transfer is due to condensation; in fact, the steam should be near saturation to limit the area required to reach the dew point.

Example 3.13 Steam heated Design flexibility into the design of a steam-heated shell and tube exchanger.

The design should ensure that all of the steam is condensed because steam exiting the exchanger represents wasted energy to boil the water. The principle for a steam heat exchanger design is shown in Figure 3.26a. The condensate is allowed to flow by gravity from the exchanger to a small vessel, so that none of the area is covered by condensate. The level of the condensate in the vessel is controlled by adjusting the liquid flow returning to the boiler process in the plant. The design in Figure 3.26b would require a vessel, piping, and an automatic PI (or P-only) controller. To reduce the cost and achieve the same performance, the typical industrial design uses a steam trap for condensate collection and return. A float steam trap is shown in Figure 3.27. When the level is low, the plug stops liquid from leaving the collection vessel; when the level is high, the plug opens and liquid flows from the collection vessel. The steam trap performs that same function as the design in Figure 3.26a, albeit via a periodic flow. Since condensate is collected in a large tank, the periodic flow rate does not influence plant performance.



a. Steam heated exchanger with condensate drum and controller
b. Steam heated exchanger with steam trap

3.26 Steam heat exchanger with flexibility and all steam being condensed

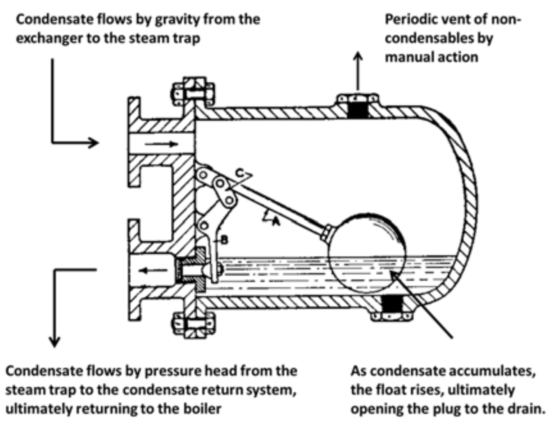


Figure 3.27 A float steam trap, one of many different steam trap principles. SugarEngineers (2019)

3.3.2 Stirred tank heat exchanger

Many processes with stirred tanks require heat transfer.

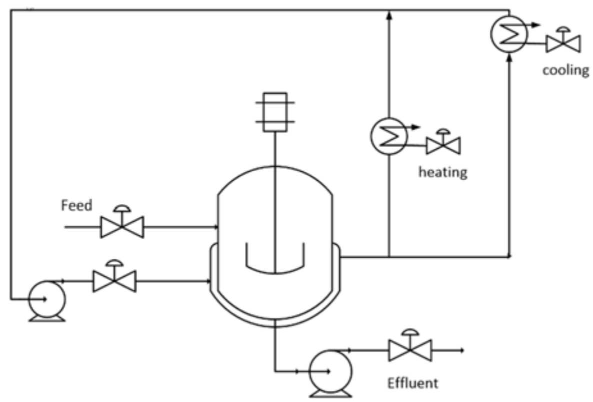
Example 3.14 Stirred tank Add flexibility to a basic stirred tank with a jacket for heat exchange.

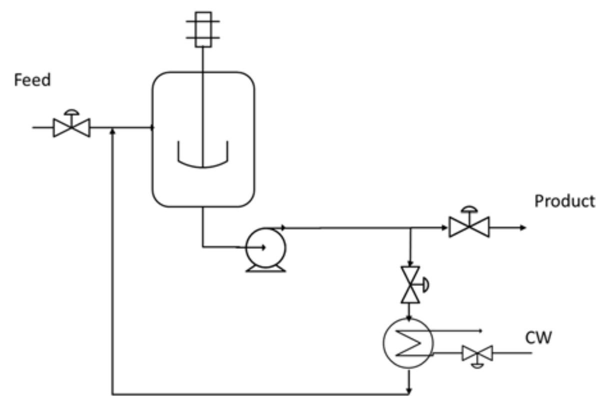
A stirred tank with a jacket for heat transfer is shown in Figure 3.28a. The design includes a circulating fluid for heat transfer with heating and cooling exchangers in the circuit. Both heating and cooling are not always required; however, this design is often needed, for example, with heating during startup and cooling during normal operation. Many other designs are possible; for example, replacing the heating exchanger with direct steam injection into water used for the heat transfer medium.

The design in Figure 3.28a exchanges heat with the tank contents through the vertical walls of the tank. For some designs, this area would be insufficient. In such cases, an external heat exchanger can be employed.

Example 3.15 External exchanger Include flexibility for a stirred tank with external heat transfer.

A design is shown in Figure 3.28b. The area for heat transfer is not related to the volume of the stirred tank, which provides the opportunity for a larger operating window.





a. Jacketed stirred tank with potential for heating or cooling b. Heat transfer with external exchanger

Figure 3.28. Stirred tank with heat transfer

3.3.3 Fired heater

Fired heaters can exchange heat to raise process fluid temperatures higher than possible with steam; temperature over 800 °C are possible. A typical fired heater is shown in Figure 3.29. Heat transfer is achieved through a combination of radiant and convective mechanisms. The tubes in the firebox are effected by radiation and convection, while the tubes in the preheat section are heated by the exiting flue gas by convection.

The basic control objectives are given in the following. (Recall that equipment protection and safety objectives are not addressed in this chapter, but they are covered in later chapters.)

- Control the fluid exit temperature (coil outlet temperature)
- Control the pressure in the fired heater (usually below ambient pressure)
- Control the oxygen in the flue gas (to ensure excess air at the burner)
- Control the feed flow to the fired heater

Manipulated variables are provided in the design; fuel valve, air intake butterfly valve, damper in the stack and feed valve. These manipulated variables can be adjusted to achieve the four control objectives. A simple, multi-loop control design in shown in Figure 3.29. This design confirms that the appropriate flexibility exists; however, it is not “industrial strength”. A more thorough presentation of fired heater control is given in API (2011).

3.3.4 Heat exchange by direct mixing

Heat exchangers are used for heat transfer without allowing contact between process streams. In limited instances, mixing is acceptable; naturally, these cases involve streams with the same or similar compositions. A schematic of a hydrocracker packed bed reactor is given in Figure 3.30. The reactions

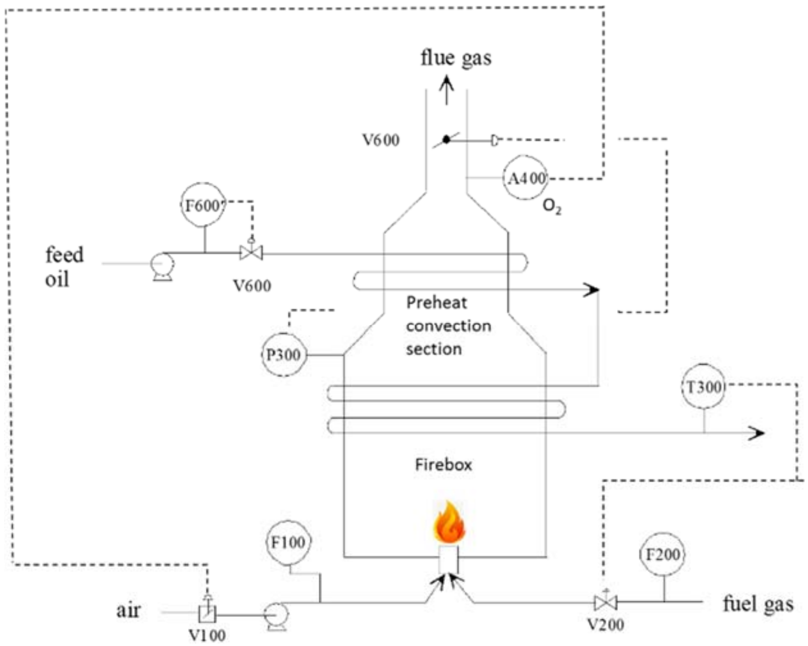


Figure 3.29 Fired heater with flexibility.

are highly exothermic, and no cooling occurs in each of the four packed catalyst beds. Therefore, good regulation of the reactor feed temperatures is critically important. Each temperature is controlled by adjusting the flow of cold hydrogen to the reactor bed; since hydrogen is supplied in excess to all reactors, the effect of the additional hydrogen is primarily cooling. Some of the hydrogen is preheated in a fired heater, so that the feed to the first reactor could have been controlled by adjusting the fuel to the heater. However, the demand for excellent temperature control of T01 could not be provided with the fired heater in the slow T10 feedback loop. Therefore, some hydrogen passes the fired heater and is used as cold quench. It is important to recognize that by-passing a fired heater is unusual; it is only done here because of the extremely tight control performance requirements.

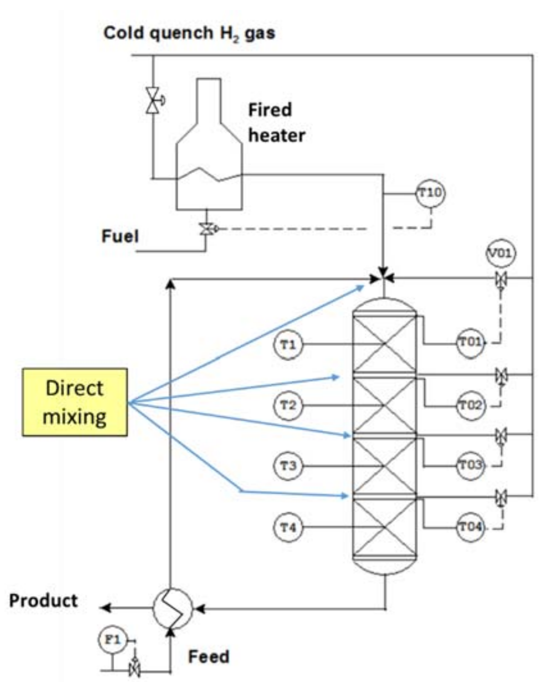


Figure 3.30 Hydrocracker using direct mixing with cold hydrogen for temperature control.

3.3.5 Heat integration

After processing, materials can be at much higher (or lower) temperatures than ambient. Considerable economic benefit can be realized by exchanging heat with process streams, thereby reducing heating (cooling) that would otherwise be achieved by processes requiring fuel or electricity consumption.

A very common form of heat integration involves feed-effluent heat transfer. The feed and product flow rates are similar, so the available and required heat transfer rates are well matched when production rate changes (they both increase/decrease together). One problematic aspect of feed-effluent heat exchange is the positive feedback effect. If a process experiences a disturbance that increases the temperature of the effluent, the process feed leaving the feed-effluent exchanger will experience a disturbance that further raises the feed temperature. This is positive feedback, i.e., a positive increase tends to further increase. In the extreme, the system can be unstable without feedback control. The common compensating factor is temperature control of the feed-effluent exchanger. A distillation tower with a feed-effluent exchanger is shown in Figure 3.31; the by-pass and tower feed temperature control essentially eliminates the positive feedback effect of thermal disturbances.

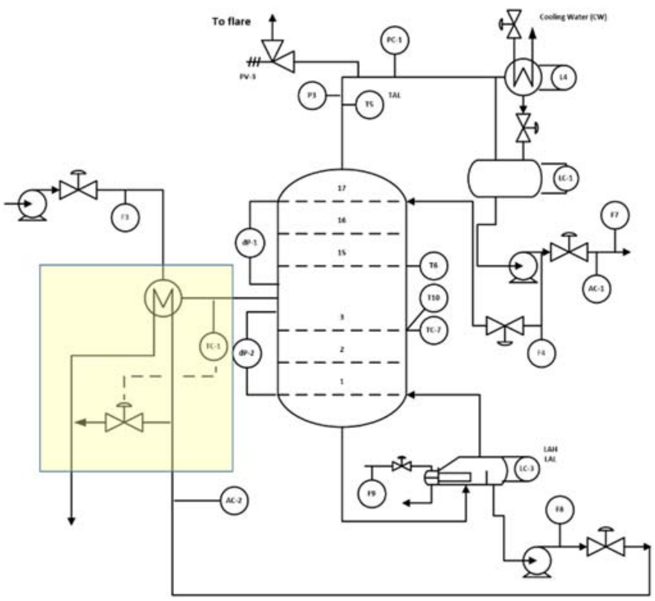
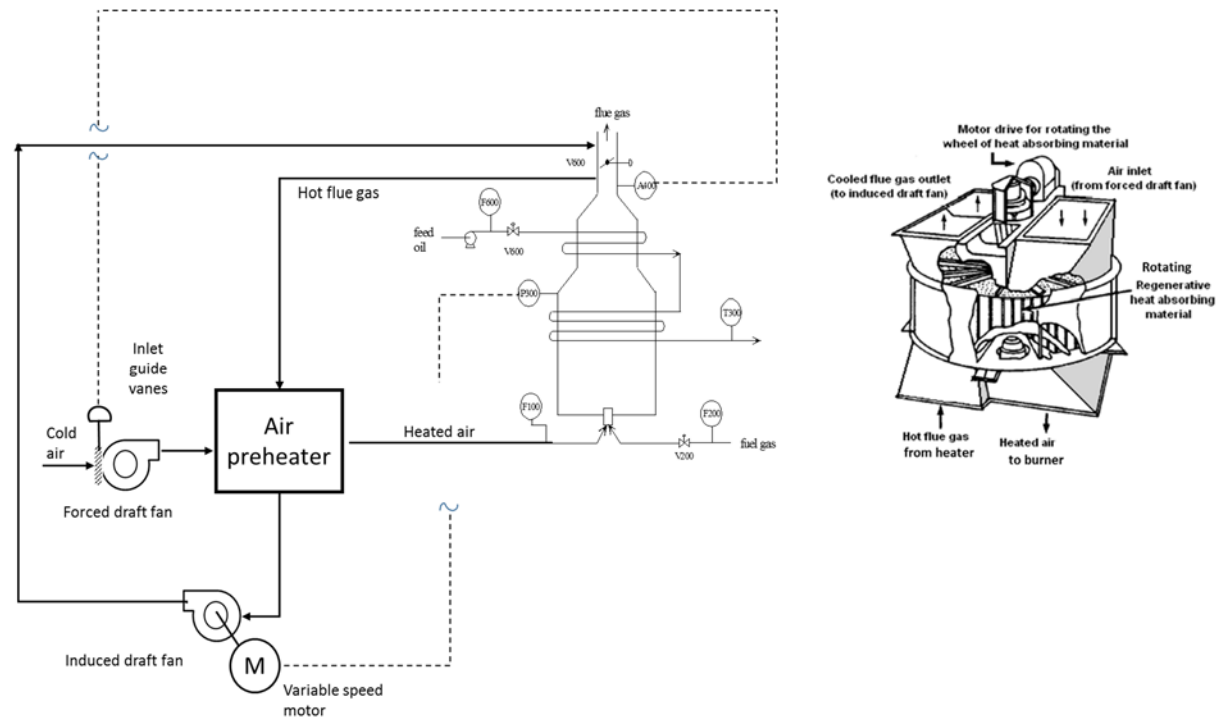


Figure 3.31 Distillation tower with feed-effluent exchanger highlighted in yellow box.

The feed-effluent exchanger principle can be applied to utility streams. As an example, the flue gas from a combustion process can be used to preheat the air used in the burner. An example is shown for a fired heater in Figure 3.32a. The combustion air is compressed in a forced-air fan operated at a constant speed, with the flow rate controlled by adjusting inlet guide vanes. These guide vanes direct the air in the direction of the fan blades and regulate flow more efficiently than an inlet dampers. The flue gas is removed from the heater using an induced draft fan that is powered by a variable speed motor. The air and flue gas exchange heat in a feed-effluent exchanger.

Because of the cost of compression and the lower-pressure operation of the fire box, the exchanger should have a low pressure drop. A typical air preheater is shown in Figure 3.32b. The heat is transferred from the hot flue gas to a rotating device; the rotating device also contacts and transfers heat to the cold combustion air. Naturally, some leakage occurs between the two streams; however, this does not introduce hazards and only slightly degrades thermal performance.



a. Fired heater with air preheat

b. Heat exchanger for combustion air preheat using flue gas (Mbeychok, 2007A)

Figure 3.32 Example of feed-effluent heat exchange with utility streams

The observant reader has noticed that the hydrocracker process in Figure 3.30 contained a feed-effluent heat exchanger. This design should include feedback control regulating the feed temperature by adjusting the by-pass around the exchanger.

Example 3.16 Hot oil circuit Installing many fired heaters in a plant can be costly. As an alternative, a design can include one fired heater with a large capacity that heats a fluid, usually an oil, that is circulated to many heat exchangers. An example is given in Figure 3.33. How is the proper flexibility ensured?

The duty for each of the heat exchangers is determined by the unit where the heat exchanger is located. These heating demands change frequently and in an uncorrelated manner. For example, each of the consumer's heat transfer is adjusted to achieve a temperature in the process in Figure 3.33. In spite of this, the hot oil system should satisfy all heat transfer demands. To achieve this goal, the following conditions must be achieved.

- The circulating flow rate must be greater than the sum of the demand flow rates.
- The heater outlet temperature must be high enough to satisfy all of the consumers demands.
- The "excess" circulating flow, which changes frequently, must by-pass all of the consumers.

To satisfy the last condition, a by-pass around the consumers is provided in the design. A controller regulates the pressure difference between the upstream and downstream pipes by adjusting the by-pass valve opening. This design has adequate flexibility.

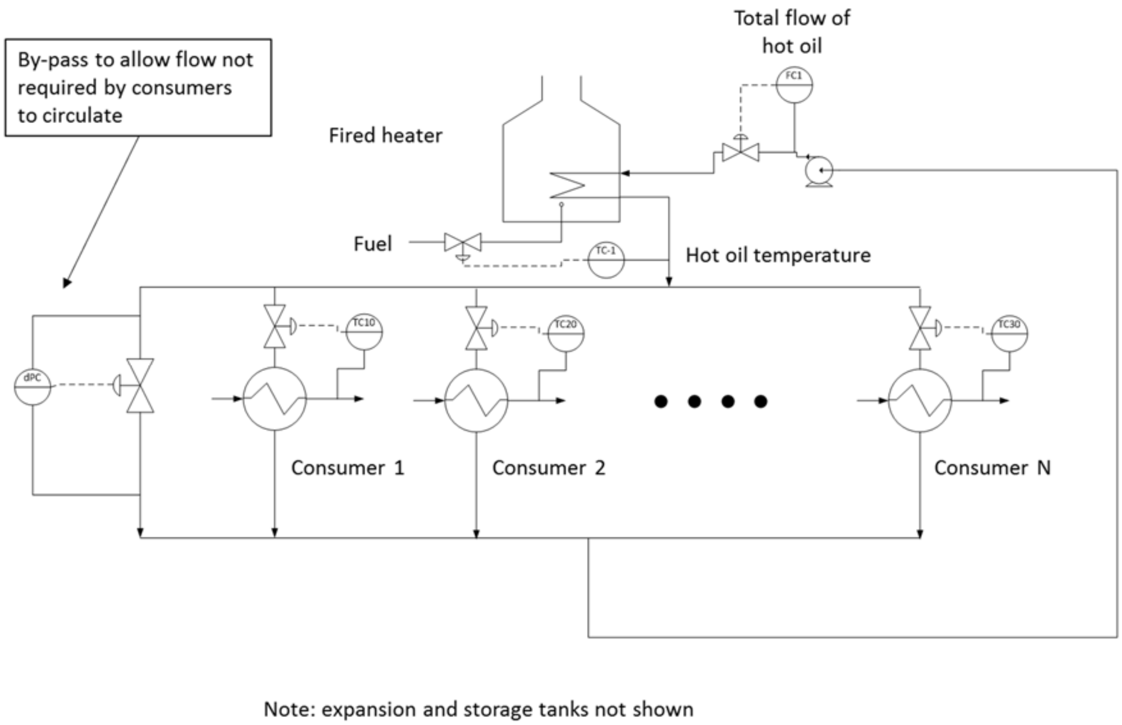


Figure 3.33 Hot oil circuit with flexibility and controllers.

3.4 Inventory and Production Rate

Process behavior is strongly influenced by how the production rate is controlled in a complex plant involving many individual units. Naturally, material must balance in the steady-state in each of the individual processes and the overall plant. The control system should use flexibility in the equipment to ensure that no long-term accumulation occurs in the processes, and to ease operation, the production rate should be established with one controller and the flow of material throughout the remainder of the process should be maintained consistent through the action of process controllers.

Production control is closely associated with inventory control. Therefore, inventory control is introduced in the next sub-section before production control is discussed.

3.4.1 Inventory control

Chemical processes contain inventory for many reasons. The following are addressed by smaller inventory capacities.

- Provide residence time for chemical reactions to occur
- Provide contact in mass transfer operations
- Provide contact for heat transfer
- Provide storage so that equipment has a continuous flow, e.g., a reflux drum that ensures continuous flow through a pump
- Provide buffering to attenuate short-term fluctuations, thereby preventing propagation of high-frequency disturbances

The following often are addressed by large inventory capacities.

- Provide material storage for periodic transport, e.g., batch delivery of raw materials and dispatch of final products
- Provide storage of intermediate products (work in progress) to decouple individual processes, e.g., enable parts of a plant to operate while other parts are temporarily shutdown

These inventories contain valuable material that in some processes is hazardous. Also, many of the common industrial liquid inventory designs are unstable. Therefore, inventory control is essential for the "small" inventories noted above. Engineering students often have a common misconception regarding the control of inventories, that is, inventories can be determined by measuring the flows into and out of a vessel, as shown in Figure 3.34. While this is conceptually correct, material flow rates cannot be measured exactly, and even small measurement errors would contribute large errors in the calculation of inventory over a long period of time, as demonstrated in the following expression that evaluates the actual inventory with the initial inventory (at time = 0) of zero.

$$actual\ inventory = \left[\sum_{i=1}^{n}(\rho_i F_i + \rho_i \varepsilon_i) + \sum_{j=1}^{m}(\rho_j F_j + \rho_j \varepsilon_j)\right] t \qquad (3.10)$$

with

F_i = measurement of inlet flow i

ε_i = error in F_i

F_j = measurement of outlet flow j

ε_j = error in F_j

ρ = density

t = time

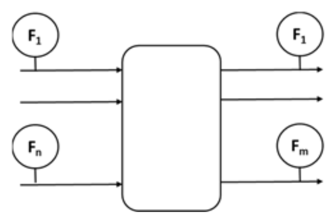


Figure 3.34 Measured flows in and out of a vessel.

The actual inventory is the integral of the difference in flows in and out. If the calculated inventory using measured flows is controlled to its desired value (e.g., half way between the low and high measurement locations) by adjusting one or more flow rates, the actual inventory is given in the following.

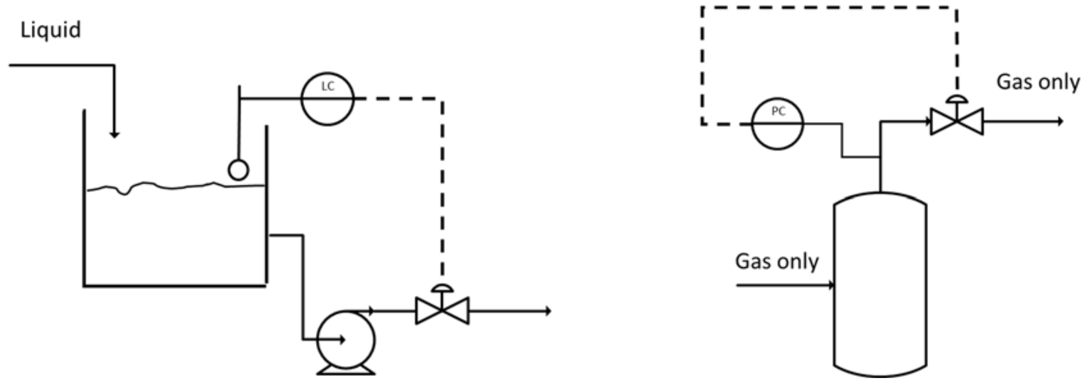
$$actual\ inventory = desired\ inventory + \left[\sum_{i=1}^{n}(\rho_i \varepsilon_i) + \sum_{j=1}^{m}(\rho_j \varepsilon_j)\right] t \qquad (3.10)$$

When the inventory calculated using flow measurements is controlled to be constant, the actual inventory grows without limit as time increases because of the measurement errors, which are not random, zero-mean due to bias measurement errors.

The accepted method for determining the inventory is to measure one of the following.

- Volume of a liquid or granular solid
- Pressure of a gas or liquid in a closed vessel
- Both level and pressure in closed vessels with both liquid and vapor
- Weight of a liquid or gas

For many designs, one or more of the flows is adjusted by feedback to control the inventory. Typical designs for level and pressure are shown in Figure 3.35a and b.



a. Controlling a liquid level b. Controlling a gas pressure

Figure 3.35. Typical inventory flexibility and control designs. Alternatively, flow rates into the vessel could be adjusted.

Some processes could have both liquid and vapor flows, requiring both level and pressure to be controlled as shown in Figure 3.36.

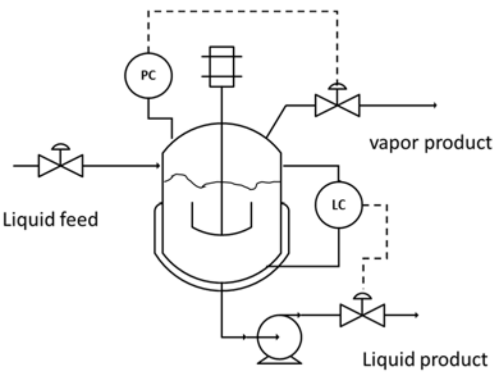


Figure 3.36. A process with flexibility for both level and pressure control.

The process in Figure 3.36 has continuous flows of both liquid and vapor that can be adjusted by feedback controllers. Some processes do not have a continuous vapor product; however, the pressure in a closed vessel should be controlled. The design in Figure 3.37 provides both an exhaust for gases produced and a source of inert gas (for example, nitrogen) for times when the pressure is below the pressure set point. The output signal from the pressure controller is transmitted to two valves; v1 is fail closed, and v2 is fail open. (This valve-failure selection ensues that upon failure, no gas enters and gas can exit the closed vessel.) The highlighted graph shows the openings of the two valves for all values of the controller output signal. This feedback design is called "split range", which is used to adjust two valves in a coordinated manner to control one variable, here pressure. The controller can be a standard PID algorithm.

Other possibilities exist for inventory control. For example, the vapor material in a closed vessel can be controlled by adjusting the rate of vapor being generated (boiled) or condensed. Examples of equipment and controls for adjusting condensation will be presented in the section on distillation flexibility later in this chapter.

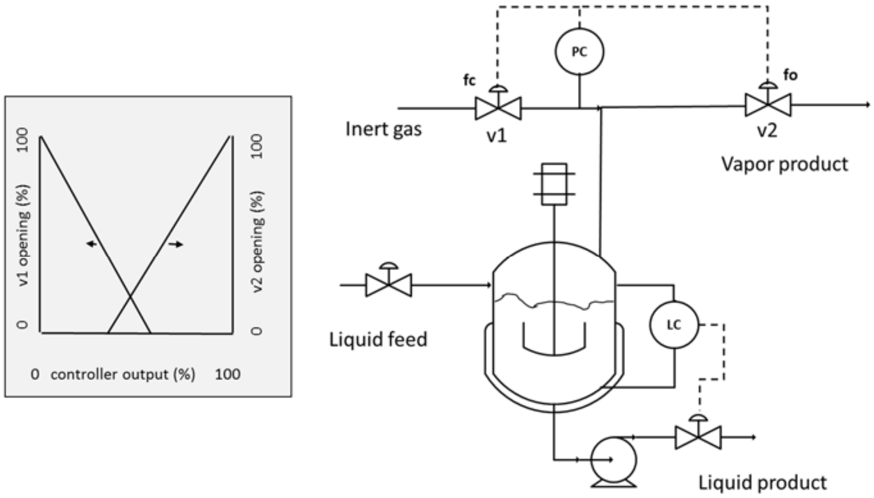


Figure 3.37 Pressure control for a closed vessel without a continuous vapor flow.

Also, the large inventories discussed in the beginning of this section are generally not controlled. Since these levels are unstable, the storage capacities must be large, so that the inventories neither run empty nor overflow. Some typical locations for large, uncontrolled inventories are shown in Figure 3.38. Feed and product inventories allow rates in and out of the tanks to be different and enable materials with different properties to be segregated. The intermediate inventories enable different process units to operate a different rates (including one to have a zero rate) for a limited amount of time, which could be hours to days. Pictures of large inventories are shown in Figure 3.39.

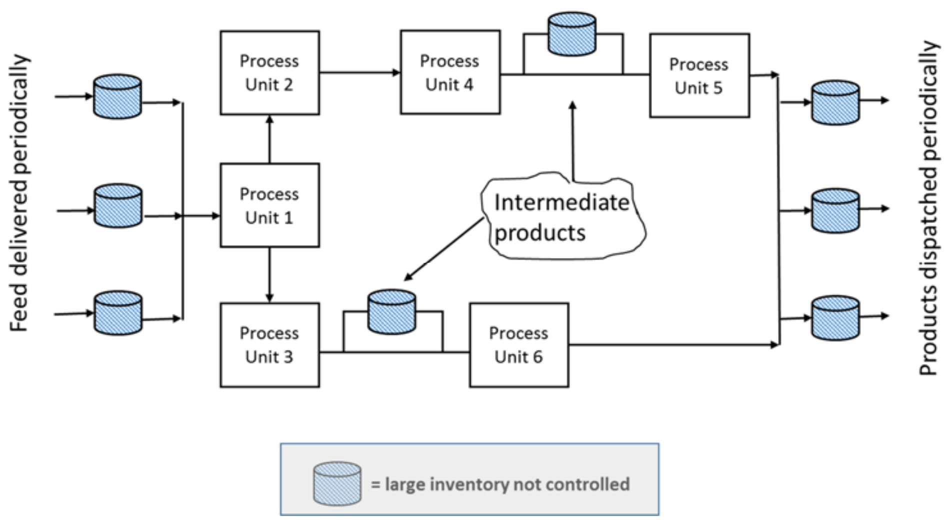


Figure 3.38 Example locations for large, uncontrolled inventory.

Ikar (2008)

Vaughn (2009)

Figure 3.39 Examples of large inventories in process plants.

3.4.2 Production rate

Production rate control follows three guiding principles.

- An integrated process should have one production rate controller.
- The rates of all units in an integrated process should match the production rate controller automatically, without actions by plant personnel.
- No component inventory should increase without limit, or to a great extent, during normal operation

Since product yields can vary, the second principle is achieved using inventory control.

Typically (although not exclusively), the production rate controller is located at either the feed entrance or product exit of the process. The two strategies are shown in Figure 3.40, in which intermediate processes are represented by tanks; naturally, the processes could be reactor, separation units, heat exchangers and so forth. The principle of how the inventory controllers are implemented would follow the designs in Figure 3.40. When the production controller is located at the feed, the strategy is termed “feed push”, and when the production controller is located at the product exit, the strategy is termed “product pull”. Many production processes use a feed push; in contrast, many utility systems, like steam, cooling water and hot oil circuits, use a product pull because they must provide the utility immediately upon request from a processing unit; examples of utility systems will be given in later sections of this chapter.

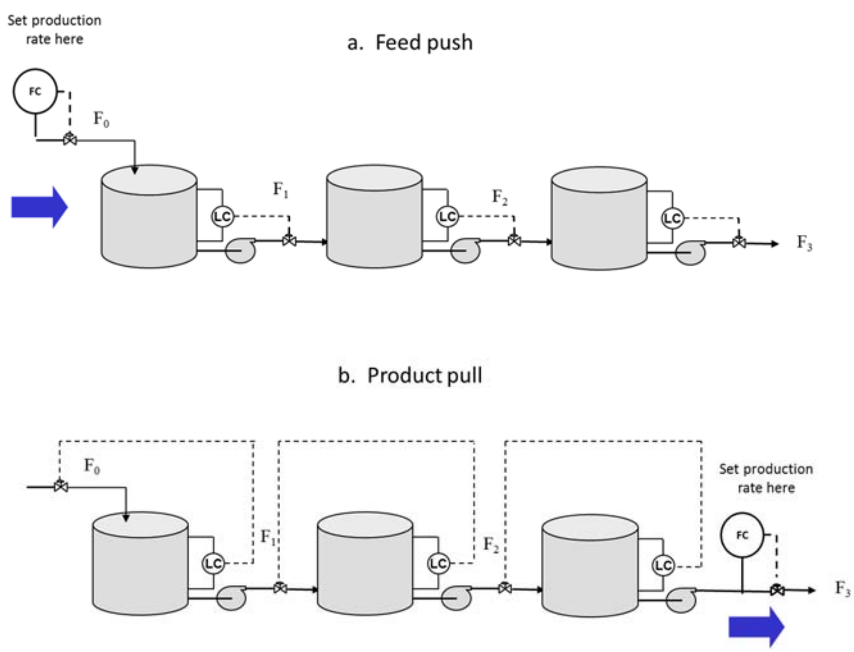


Figure 3.40 Production rate control push and pull strategies

The principles of production and inventory control are combined for an integrated process. An example for a petroleum hydrodesulphurization process is given in Figure 3.41. The feed enters in the left of the figure, and the product and by-product exits on the right of the figure. The flexibility is discussed in the following, with each discussion referencing a numbered location in Figure 3.41.

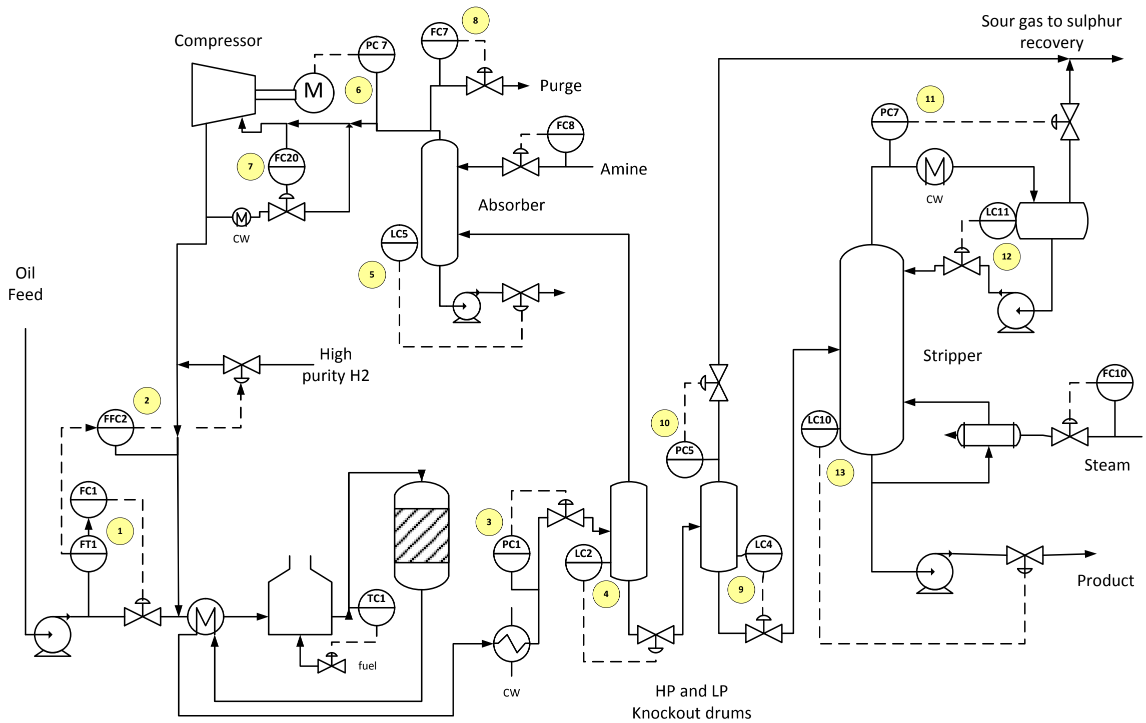


Figure 3.41 Production flexibility for a hydrodesulphurization process.

Location number	Discussion
1	The design implements feed-push production control, because the product rate can vary. The controller FC1 maintains the oil feed to the reactor at a constant value. Because of this feed-push strategy, the inventories for downstream vessels must adjust their exit flow rates.
2	The reaction chemistry indicates that the feed hydrogen should be maintained in a ratio to the oil flow rate. The feed hydrogen is the sum of the recycle and the fresh, high purity hydrogen. The FFC-2 (flow fraction controller) adjusts the fresh feed valve to achieve the desired ratio of the two measured flows.
3	The pressure in the reactor is maintained by PC1.
4	The high-pressure separator (or knockout) drum has liquid and vapor inventories. The liquid inventory is controlled by adjusting the valve in the liquid exit pipe. No pump is required because of the pressure difference between vessels.
5	The vapor from the high-pressure separator flows to the absorber where Sulphur compounds are removed. Amine absorbing agent is introduced at the top of the absorber, and the liquid inventory at the bottom is controlled by adjusting the valve influencing the exiting liquid.
6	The pressure at the suction of the recycle compressor is controlled by adjusting the speed of the driver, which in this case is a motor. The design returns all of the vapor from the high-pressure separator (except for the purge) to the reactor. Setting the suction pressure defines the pressures in the absorber and high-pressure separation drum.
7	A flow controller (FC20) ensures a flow through the compressor that is greater than the limit at which surge would occur.
8	The recycle loop would be closed without the purge stream, so that small vapor impurities and by-products would eventually build up in the recycle. Therefore, the purge is included in the design; FC7 determines the purge flow rate.

9	The low-pressure separation drum has liquid and vapor inventories. The liquid inventory is controlled by adjusting the valve in the liquid bottoms exit pipe. No pump is required because of the pressure difference between vessels.
10	The vapor inventory in the low-pressure separator is controlled by adjusting the valve in the vapor exit pipe.
11	The vapor inventory in the stripper is controlled by adjusting the valve in the vapor product pipe leaving the overhead reflux drum. The sour gas is subsequently processed to recover the sulphur.
12	The liquid inventory in the reflux drum is controlled by adjusting the reflux control valve.
13	The liquid inventory at the bottoms of the stripper is controlled by adjusting the product flow valve. This is the end of the "push" in the feed-push design.

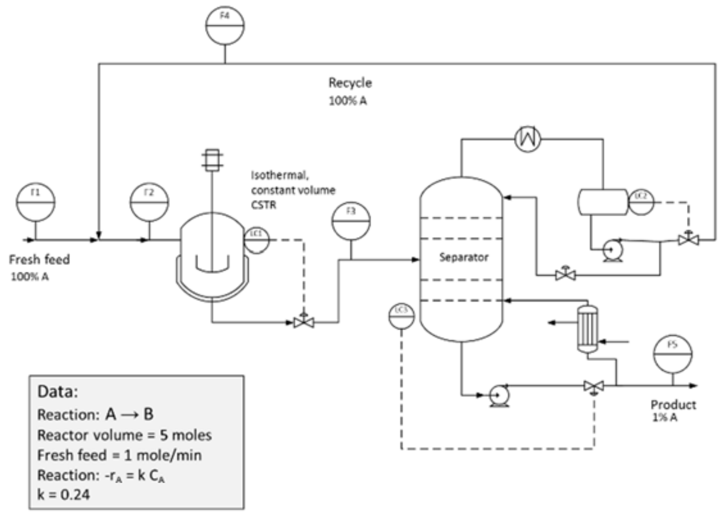
The liquid inventory in the vessels are in the "small" category discussed above. The holdup times for the vessels, the volume divided by the design flow rate, would be in the range of 5 to 15 minutes. With such small times, no opportunity exists to stop integrated units without stopping the entire process. However, the inventory is essential to ensure a smooth and nearly constant flow to integrated units. In addition, the inventory can be used to attenuate high-frequency flow disturbances entering the vessel, so that the flow adjusted by the level controller will experience the high-frequency variability with much lower amplitude. This is discussed in detail and controller tuning guidelines are given in Marlin (2000, Chapter 18).

3.4.3 Component inventory

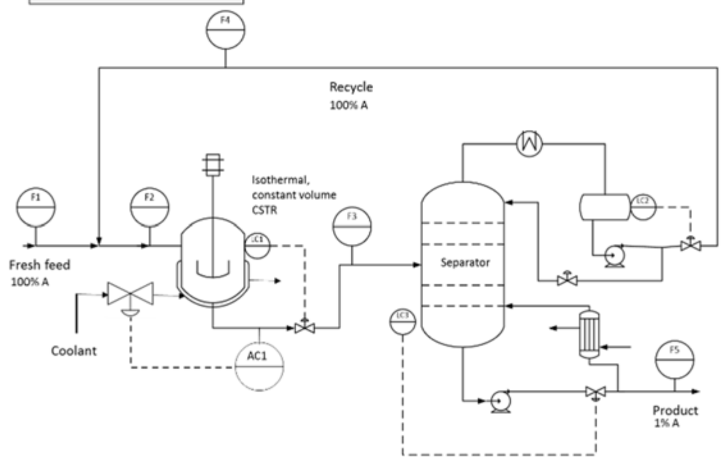
Some further discussion about the potential for component buildup is warranted. The potential existed in the recycle loop for the hydrodesulphurization process just discussed; without purge, the impurities would have increased without limit because there was no exit for the vapor impurities that would not have condensed in the high-pressure separation drum. Put another way, the dynamic system is unstable. This condition is relatively easy to identify and the solution of a purge is straightforward; most chemical engineers learned this design technique in the first course on material and energy balances. However, some processes have a buildup of one or more components even when some of the component exits the process; this situation is not as easy to identify and can disrupt the plant operation.

We will introduce conditions where the second type of buildup, which is limited but disruptive to plant operation, occurs using an example. A chemical reactor with separator and recycle is shown in Figure 3.42a. The recycle is pure reactant (A), while the product stream from the separator bottoms contains 1% reactant (A). Therefore, some reactant exits the process continuously, and the dynamic system is stable. However, the dominant mechanism for reduction of reactant in the system is the chemical reaction occurring in the reactor, which depends on the concentration of reactant, flow rate, liquid volume and temperature. Base case operating data for the process is given in Figure 3.42a; the base case value for the ratio of recycle to fresh feed to the reactor is 4.66.

What would be the steady-state response of this process to a change in reaction rate, here represented by a change to the rate constant (k), which could be caused by a small change in temperature or feed impurity? The results are shown in Figure 3.43. It is clear that even small changes in reaction rate constant can lead to large changes in the recycle ratio. This high sensitivity is caused by the recycle and is often termed the "snowball effect" because the recycle increases rapidly, like a snowball accumulating additional snow as it rolls down a snow-covered hill. The high sensitivity to disturbances is undesirable because of the large equipment capacities required in the recycle process, here the reactor and separation unit.



a. Design subject to strong snowball effect



b. Design without snowball effect

Figure 3.42. Reactor with separator and recycle with flexibility and control.

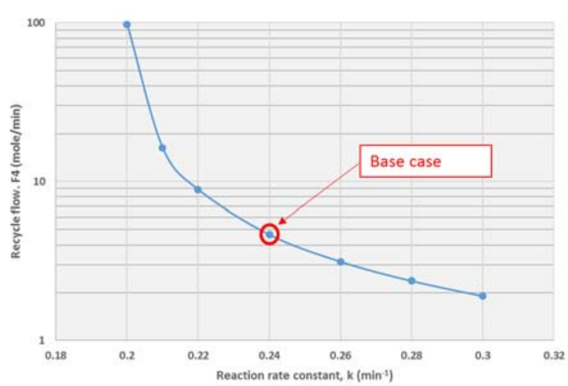


Figure 3.43. Snowball effect of reaction rate disturbance on recycle flow rate for process in Figure 3.42a.

There are several ways to improve the behavior of the process. One improvement is shown in Figure 3.43b, in which the reactor concentration is controlled by changing the reactor temperature. With this modified control system, the steady-state recycle flow rate is constant for the rate disturbance. This is much better behavior and requires smaller equipment capacity.

The snowball effect is discussed in detail with many examples in Luyben, Tyreus and Luyben (1999), and a process example with dynamic responses is presented in Marlin (2000, Chapter 25). Please recognize that the snowball effect does not occur in all processes with recycle.

3.5 Unit operations

The approaches explained in the previous sections in this chapter are applicable to many processes. However, the final designs are not obvious to the novice practitioner. Therefore, designs for a few common unit operations are discussed in this section.

3.5.1 Boiler and steam system

Steam is used widely in the process industries for power and heat. A plant that uses steam for power in turbines for pumps and compressors (and potentially for generating electricity) and uses the exhaust steam for heating are very efficient. Since process plants have these dual needs, they often have large steam generation and distribution systems.

A steam generation and distribution system must respond quickly to the demands of many consumers in the processes served. The demands may change rapidly due to changes in process operation, for example, throughput adjustments. In addition, demands can change by large amounts due to equipment startup or shutdown. An overview of such a system is given in Figure 3.44. The interconnecting piping and valves distribute the steam as needed, and the boilers must generate the steam required to satisfy all distribution demands. The consumers are of higher priority than the boilers; therefore, the steam system is a "pull system", in which each consumer takes the amount of steam it requires.

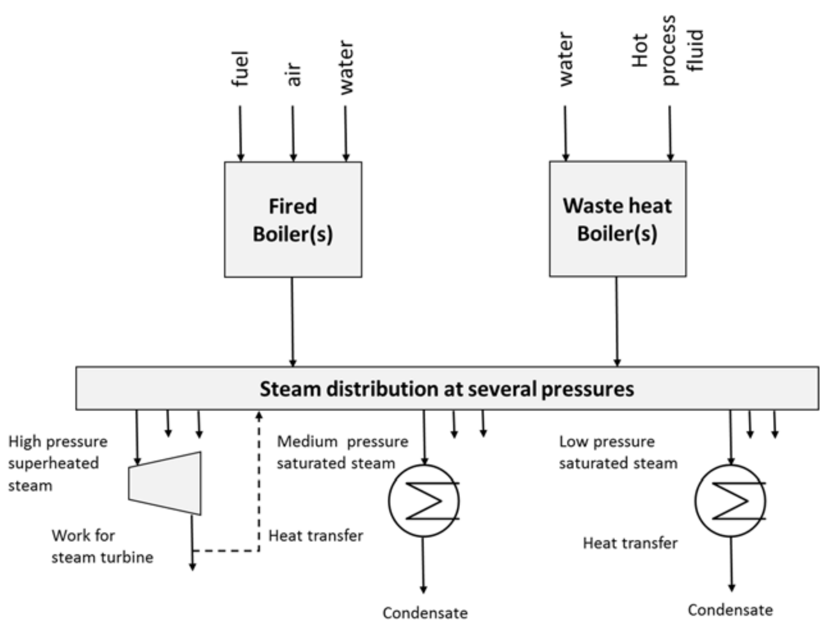


Figure 3.44. Schematic representation of boiler and steam system. This is a pull production system.

Fired Boiler: A drawing of a fired boiler is given in Figure 3.45. Water from the boiler drum descends in the downcomer and ascends in the riser where it is partially vaporized. The flow occurs because of the differences in density between the water in the downcomer and the water-steam mixture in the riser; the water is not pumped. Although only one loop is shown in Figure 3.45, many riser tubes cover the walls of the boiler firebox to increase the area for heat transfer. Saturated steam leaving the drum is superheated by heat transfer with the exiting, hot flue gas. Since the superheated steam temperature is important, flexibility is introduced by adding boiler feed water to the superheated steam. Water entering the drum is also heated by heat transfer with the flue gas. Air is provided to the burner using a forced draft (FD) fan, and flue gas is removed using an induced draft (ID) fan. Air is preheated by heat transfer with the flue gas. The temperature of the flue gas leaving the air preheater must be maintained above the acid dew point to prevent corrosion. Therefore, a valve allows cold boiler feed water to partially by-pass the air preheater.

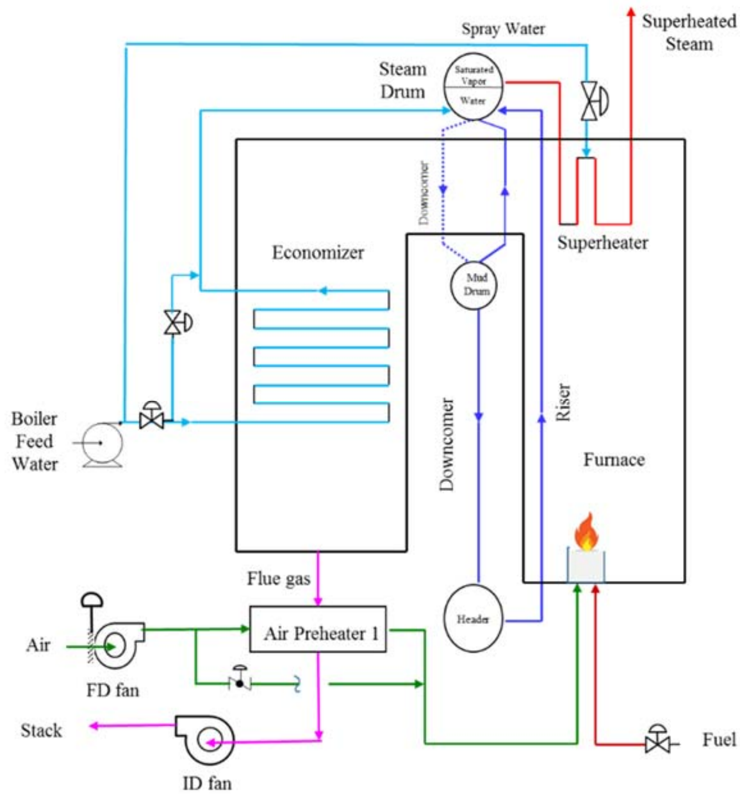
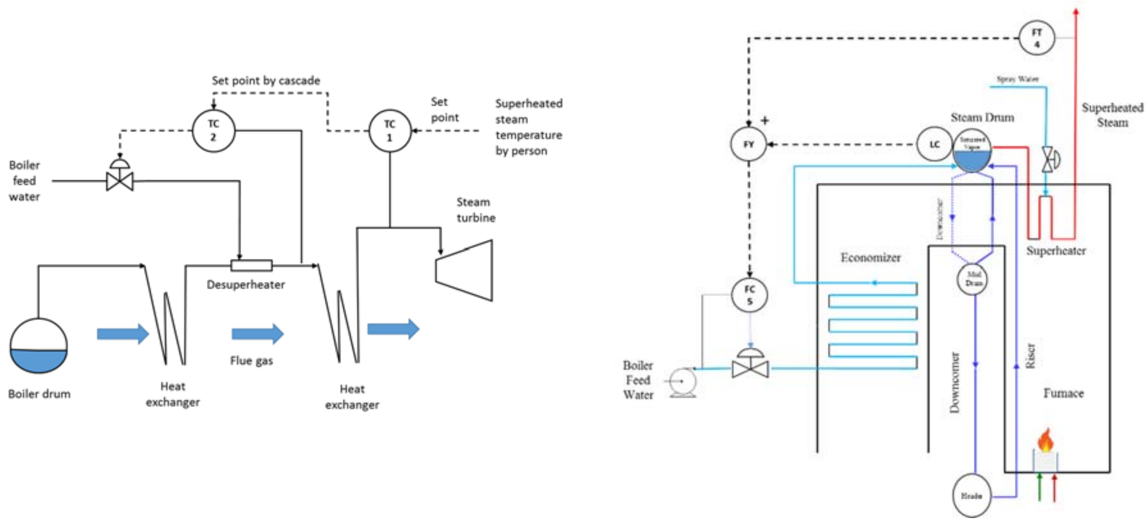


Figure 3.45. Fired boiler with flexibility.

The efficiency of turbines is increased by increasing the steam superheat temperature, but too high a temperature can damage the turbine blades. Therefore, the superheated steam temperature must be controlled. The equipment design and control system is shown in Figure 3.46a. Since the flue gas and steam flows cannot be adjusted, the common approach for introducing flexibility is to add water to the steam being superheated; the vaporization of the water cools the steam. The desuperheater injects the water so that the vaporization occurs rapidly. As shown in the figure, the heat exchanger can be separated into two zones. The temperature after the first zone of the desuperheater (TC2) is measured and controlled. The final superheated temperature (TC1) is controlled in a cascade design by adjusting the set point of TC2. The two feedback controllers can use the standard proportional-integral-derivative (PID) algorithm. The cascade design provides faster response to changes in the flue gas and steam flow rates than a single-loop (TC1 directly to valve) design. Feedforward for the steam flow rate can be added , if this basic design does not provide adequate performance.

The steam drum level is a very important variable. If the level falls too low, the water circulation in the downcomer-riser will be too low or stop; low water level can lead to rapid overheating and severe damage to the riser tubes. Too high a level could lead to water in the steam pipe. Since no deadtime exists between adjusting the water feed to the drum and the response of the level, one might conclude that level control is straightforward. However, complex dynamic behavior introduces challenges that require a unique control design for the fired boiler level controls. The complex dynamics involve the “swell” effect. When a steam pressure decreases rapidly, the water in the drum, downcomer and riser partially flash to vapor. This flashing occurs throughout the water inventory, and it pushes water into the boiler drum, which causes the level sensor to record an increase in water level, although the amount of water in the boiler is actually



a. Superheat temperature flexibility and control b. Fired boiler level flexibility and control
Figure 3.46. Details on fired boiler flexibility and control.

decreasing. In response to a decreasing pressure, the main steam pressure controller increases fuel firing, which will further increase water vaporization and decrease water inventory. Because flashing causes the measured level in the drum to increase, the level controller would decrease the flow of boiler feed water just when an increase is required. (A similar, but opposite, effect occurs when the pressure decreases.) This swell effect has been modeled and studied empirically by Astrom and Bell (2000).

The standard solution to compensate for the misleading level measurement during disturbances is shown in Figure 3.46b. The feedback level controller is retained and enhanced by a feedforward correction based on the steam measurement. The feedforward controller increases the water flow when the steam flow has increased. Dynamic compensation can be added to the feedforward, if this steady-state feedforward design does not adequately reduce the effects of swell. The resulting design is termed "three-element level control" because it uses three sensors for the level, steam flow and water flow.

The boiler steam pressure is controlled by adjusting the fuel to the burner. Naturally, sufficient air must be present at the burner to combust the fuel, and this requirement should be satisfied during both steady-state and dynamic operation. One could regulate the ratio of air to fuel to achieve the required excess air; however, flow measurement errors would be excessive to achieve an air flow rate in slight excess of the stoichiometric requirement. To accurately achieve excess air, the concentrations of oxygen and carbon monoxide in the flue gas are measured in real-time. The requirement for oxygen is 1-2 percent. Carbon monoxide is generated when incomplete combustion occurs, which can happen at one of the burners while other burners have sufficient air; carbon monoxide is controlled at or below 100 ppm in the flue gas. Therefore, the following flexibility-related equipment are required.

- Control valve for fuel flow
- Manipulated variable for air (damper, guide vanes, or variable speed motor)
- Measurement of oxygen in the flue gas
- Measurement of carbon monoxide in the flue gas

One additional consideration is important in the design. As the pressure controller continually changes the firing in the boiler, excess air should be present, even when the fuel and air flow rates have small and differing delays in their responses to commands. During dynamic operation, air should increase before the fuel increases, and fuel should decrease before the air decreases. This requires a complex control system to ensure safety during transients. The control system must compare air and fuel flow rates expressed in the same units; for example, fuel can be converted to air units by multiplying the fuel measurement by the appropriate air/fuel ratio. The air/fuel ratio depends on the fuel being combusted and the measurements being used; therefore, it cannot be a constant value determined from theoretical chemistry. The flue gas analysis is used by a feedback controllers (AC1 and AC2) to continually update the appropriate air/fuel ratio. The resulting control design, termed “cross-limiting control”, is given in Figure 3.47. Note the simplicity of the calculations involved in implementing this complex strategy; the entire strategy could be implemented in analog calculating equipment that was used before digital control computers were available in the 1960s.

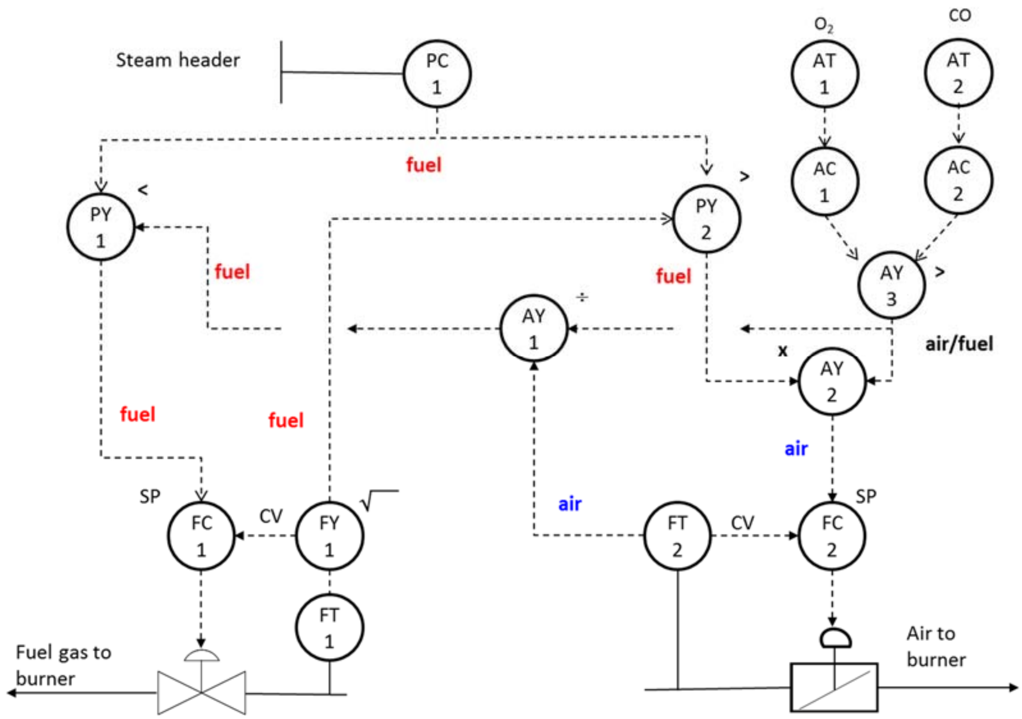


Figure 3.47. “Cross limiting” firing control designed to ensure excess air during steady-state and transient operation

Waste Heat boiler: Process plants often have streams at high temperatures that must be cooled before storage or transport to subsequent processes or customers. These streams could be cooled using cooling water, but this practice would waste energy at a high value, i.e., a high temperature. One manner for using this high-temperature resource is to introduce a heat exchanger that generates steam, which is usually termed a “waste heat boiler”. Typically, the system is designed to generate the maximum amount of steam possible, with the generation by fired boilers in the plant adjusted to balance the total generation with the consumption. A review of waste heat boilers is given in Jouhara et.al. (2018).

A waste heat boiler is shown in Figure 3.48. The steam pressure is controlled by adjusting a valve in the steam exit pipe. This allows the maximum steam generation. Since the pressure is tightly regulated, the drum level does not experience the “swell” effect that made level control challenging in a fired boiler. Therefore, level can be controlled by feedback without feedforward. Superheating can be added to the design if needed.

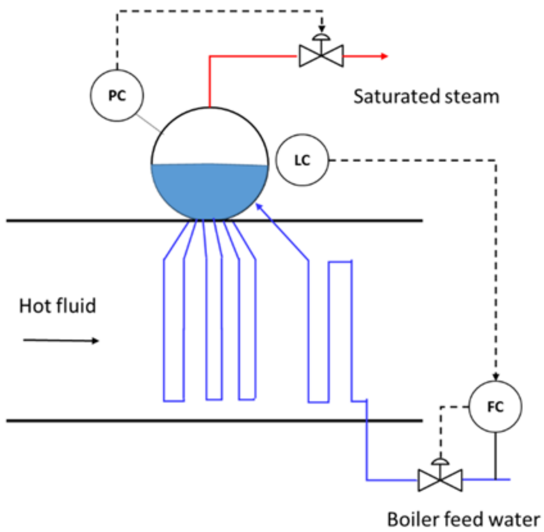


Figure 3.48. Waste heat boiler with flexibility and controls.

Steam distribution: The boilers and interconnecting piping must provide steam for many, distributed demands; so, how is this coordination of generation and consumption achieved? As we have learned in the section on production control, measuring the demands directly is subject to errors. Therefore, the coordination is through controlling the inventories of steam, i.e., the pressure in the pipes used to distribute steam to the consumers. Maintaining the pressures at their specified values ensures that steam is available at the flow rate and pressure required.

A simplified boiler and steam system is shown in Figure 3.49. Only one boiler is shown; however several fired and waste heat boilers could be included in the process. In addition, only a few consumers of steam are show; however, many more turbines and heat exchangers could be present. It is important to recognize that each of the consumers decides independently how much steam to consume through its process control system to meet power and heat transfer requirements. A short description is given for some of the equipment.

- The turbines satisfy power requirements by adjusting the valve at the inlet to the turbine. Turbines can be used to power compressors and pumps and to generate electricity.
- Some turbines will have extraction of steam to lower-pressure headers. The steam leaves the turbine partway through the length of blades, so the work per kilogram of steam is lower than for steam traveling to the end of the turbine.
- Some turbines will exhaust steam to a lower-pressure headers
- Some turbines exhaust steam near atmospheric pressure, where the steam is condensed using cooling water.
- Heat exchangers use medium and low-pressure steam for heat transfer. The steam flow is controlled by the individual processes to achieve desired temperatures or pressures. Condensate leaves these exchangers and is collected for return to the boilers.

To reiterate, this is a "pull" production control system. A simple, partial control system is shown in Figure 3.47 to demonstrate how the demands are transmitted via the header pressure controllers. The figure also contains valves (v100, v200, v300) that can pass steam directly between headers. These are used to release steam if the pressure is too high or (for v200 and v300) to allow flows into the header if the pressure is too low. The control systems including these "letdown" valves is complex, and its design is an question at the end of this chapter.

Flows through the letdown valves represent inefficiencies, so their use should be minimized by adjusting steam consumption where possible. Recalling that consumers must obtain the work or heat required, changing the steam consumption must involve replacing the consumers requirement with an alternative source. For example, a large pump could have the option of providing power by either a steam turbine or electric motor. This action would not typically be automated; it would be implemented by plant personnel infrequently.

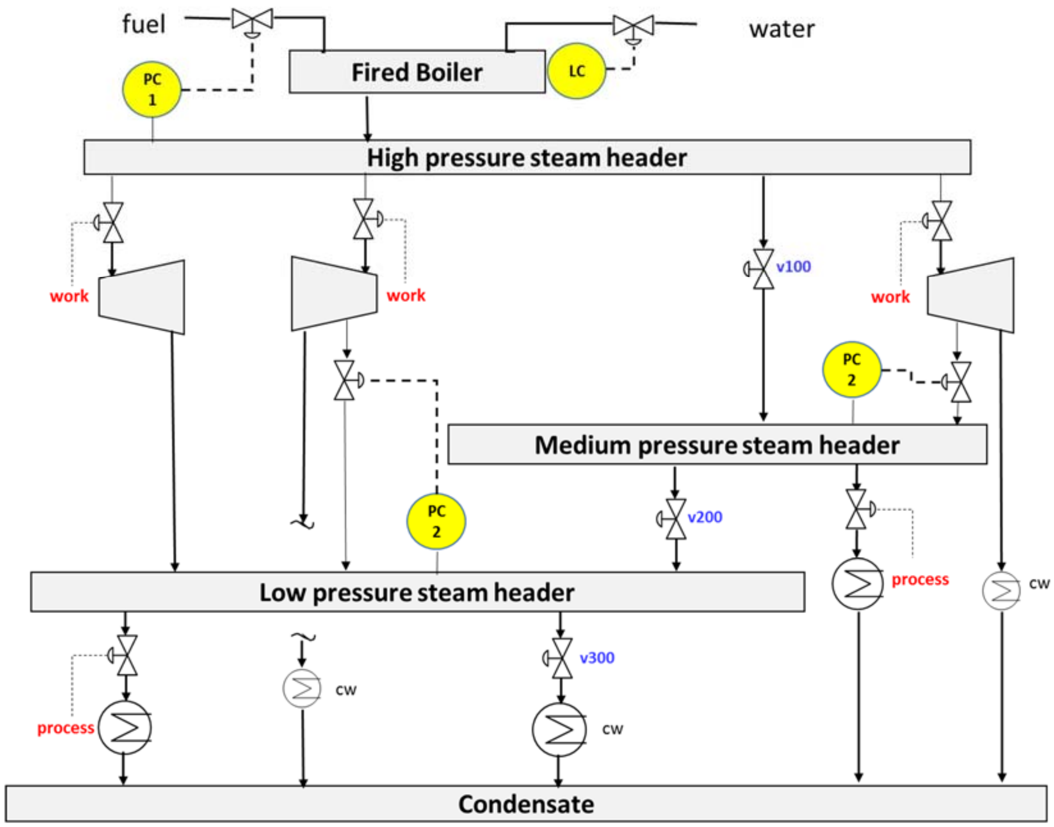


Figure 3.49 Steam system with flexibility and partial control design

3.5.2 Distillation

Distillation is a very important separation method for the process industries. Distillation design and operation has a strong impact on product purities and on compositions of intermediate streams in a process. Also, distillation requires a large operating expense for utilities like steam for reboiling and in some cases, refrigeration for condensing. The U.S. Department of Energy has estimated that distillation is responsible for forty percent of the total energy consumption in the petroleum and bulk chemicals industries (DOE, 2001). Even a cursory coverage of distillation design and operation would require several books; good references have been prepared by Kister for design and operation (1990, 1992), and by Liptak for control (2005). This short coverage will highlight some key flexibility issues and designs.

One key issue is the management of inventories. Large quantities of liquid are vaporized in the reboiler and in some cases, in the feed. Much or all of this vapor must be condensed and withdrawn as liquid product or returned to the tower as reflux. Therefore, managing vapor inventory is also important. As we have seen previously, managing vapor inventory is achieved by controlling the pressure. A few of the more common approaches to pressure control are given in the following examples.

Example 3.17 Vapor product Design a pressure control system for a process with a continuous vapor product.

The design in Figure 3.50a provides pressure control for distillation with a large, continuous flow of vapor product. The coolant to the condenser is maximized, because this design is appropriate when as much overhead vapor as possible should be extracted as liquid product. The composition of the heavy key in the liquid distillate can be controlled by adjusting the reflux flow rate.

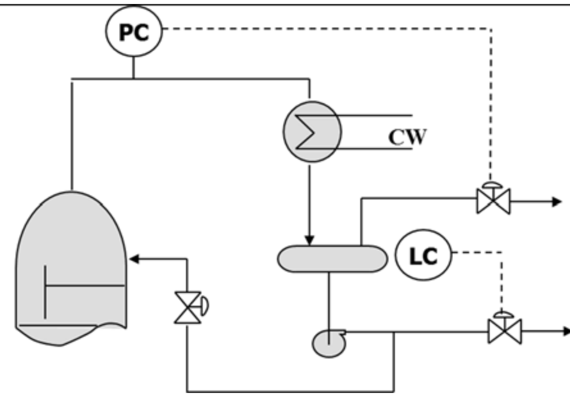
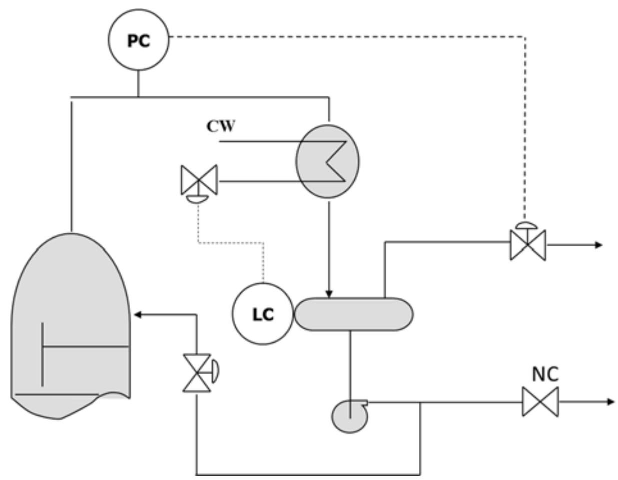


Figure 3.50a

The design in Figure 3.50b provides pressure control for distillation with a large, continuous flow of vapor product and zero liquid overhead product. The accumulator drum level controller adjusts the condenser cooling, so that only enough vapor is condensed to supply the reflux flow rate and no more. This design shows the cooling water flow rate being manipulated, but any other approach for adjusting the condenser duty would be acceptable, and many would be preferred (as discussed in the following examples).



Figue 3.50b.

The design in Figure 3.50c involves compression of the vapor product. The pressure in the distillation tower is controlled by adjusting the work performed by the compressor. The design in the figure adjusts the speed of an electric motor. Flexibility could be provided by other possible adjustable variables, such as steam turbine speed or recycle around a constant speed compressor

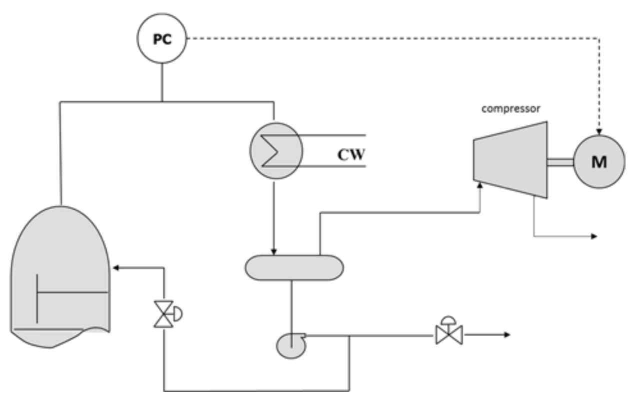


Figure 3.50c.

Example 3.18 No vapor product Design a pressure control system for a process with no vapor product.

The most straightforward method for controlling pressure is to adjust the coolant flow rate through the condenser as shown in Figure 3.50a. However, this approach is not often used when the coolant is cooling water because low flow rates and high exit temperatures (above about 50 °C) can lead to rapid fouling of the exchanger.

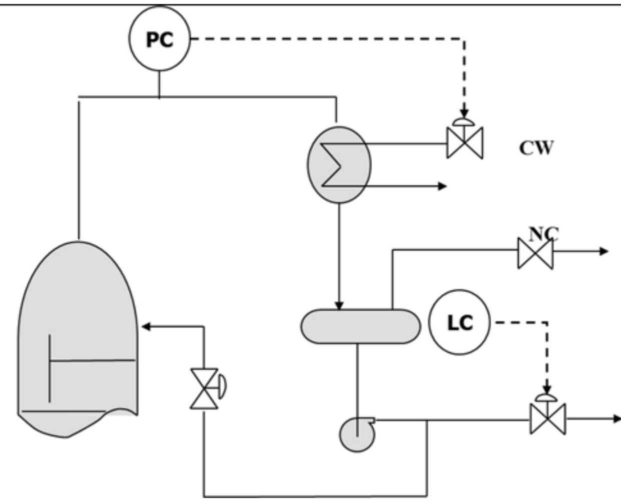


Figure 3.51a

A common manner for achieving complete condensation of the overhead vapors is a flooded condenser as shown in Figure 3.51b. A valve is located on the process side at the outlet of the condenser, resulting in the condenser being partially filled with liquid condensed in the exchanger. The pressure controller manipulates this valve; in the event of pressure above the set point, the controller tends to open the valve, which reduces the condenser level and uncovers more area for condensation. Therefore, the approach adjusts the area to change the duty! In this design, the condenser must be above the accumulator drum, and the equalization line to the accumulator is essential so that the accumulator pressure is regulated.

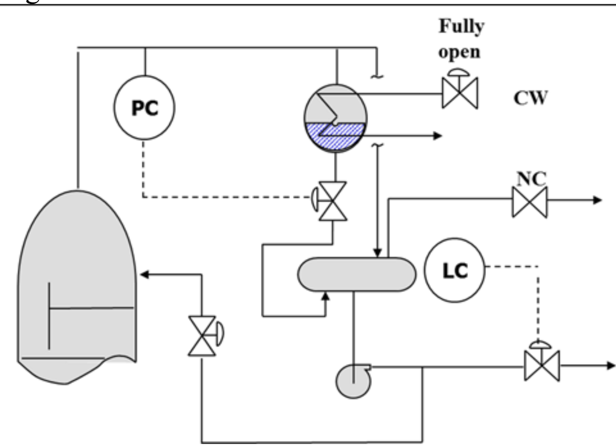


Figure 3.51b.

A similar design shown in Figure 3.51c is also quite common. The principle is the same as the previous design, i.e., the area for condensation is changed to control the tower pressure. The difference is the valve in the exchanger by-pass pipe, which is adjusted to control the accumulator drum pressure (below the tower pressure value). With this modification, the condenser does not have to be located above the accumulator drum, saving capital cost.

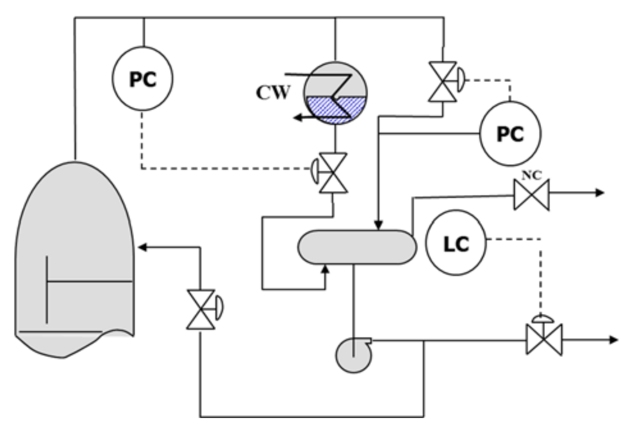


Figure 3.51c.

In some cases, air is used as the cooling medium. Airfin condensers can have a lower overall cost, but they require a larger area, must be elevated, and require more maintenance. Pressure control can be achieved by adjusting the airfin blade (motor) speed, blade pitch, or louver position.

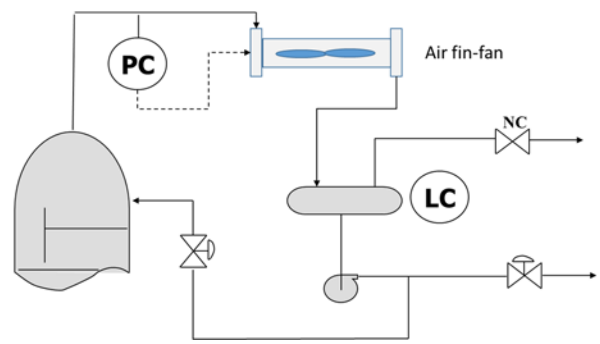


Figure 3.51d.

Example 3.19 Condensing with refrigeration
Design a condenser when the coolant is a refrigerant.

As heat is transferred from the process to condense the vapor, the liquid refrigerant is vaporized. The rate of heat transfer depends upon the area of heat transfer to the liquid refrigerant, and the area depends on the level of refrigerant in the exchanger. The pressure controller adjusts the set point of the exchanger level controller in a cascade design. If the tower pressure were high, the pressure controller would increase the set point of the level controller to increase the area for vaporization.

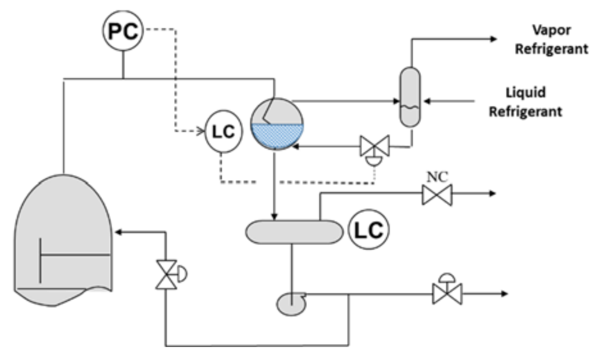


Figure 3.52a

An alternative strategy maintains the condenser level at its maximum at all times. In this design, the temperature difference is changed to influence the rate of condensation. The refrigerant boiling temperature depends on the refrigerant pressure. Therefore, the tower pressure controller adjusts a valve that affects the refrigerant pressure. If the tower pressure were high, the tower pressure controller would increase the opening of the refrigerant vapor valve, which would lower the refrigerant temperature and increase condensation.

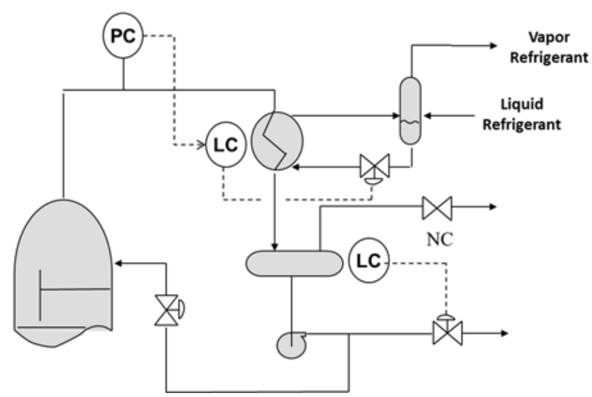


Figure 3.53b.

Additional designs for distillation pressure control are described by Sloley (2001).

Vapor in the distillation process is generated by the reboiler. The selection of the appropriate reboiler design is discussed with recommendations by Love (1992). The design flexibility for the reboiler and the bottoms inventory should be decided in an integrated manner. A few examples are given in the following.

Example 3.20 Kettle reboiler Design the flexibility for a kettle reboiler.

A design is shown in Figure 3.54, in which the bottoms liquid flows by gravity to the external kettle reboiler. The reboiler has two segments; one for heat transfer and a second quiescent vessel to the right of the weir that holds inventory to provide a smooth, gas-free feed to a pump. Any heating medium can be used in the coils; the figure shows steam with a steam trap at the exit of the heat exchanger coils.

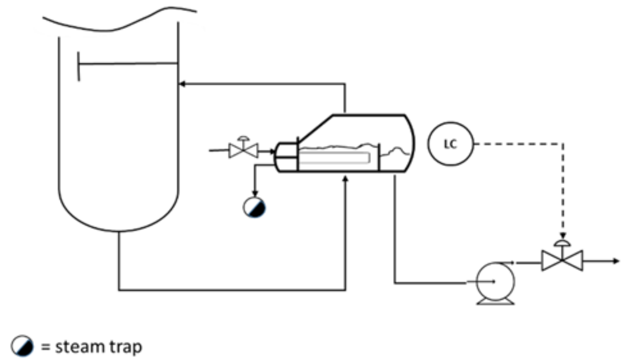


Figure 3.54.

Example 3.21 Thermosiphon Design the flexibility for a natural circulation thermosiphon reboiler.

The design and flexibility is shown in Figure 3.55. Liquid is collected from the last tray; this liquid is split between the reboiler and an overflow that falls to the bottoms inventory. Liquid flows to the reboiler, where it is partially vaporized; the fluid returns to the tower below the first tray. The height of the liquid collector relative to the heat exchanger provides the driving force for flow. The heating medium flow rate is regulated by a control valve.

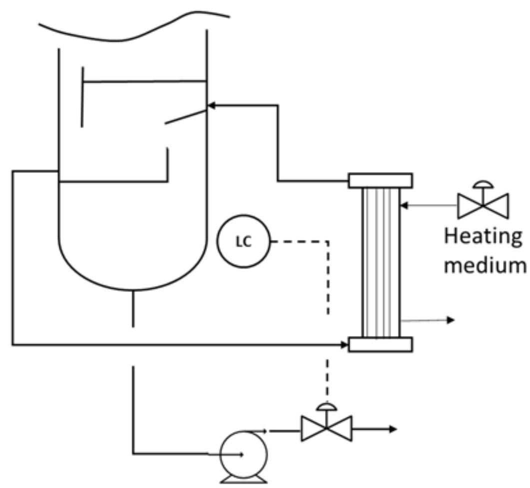


Figure 3.55.

All of the approaches can be combined in the design with flexibility and control for a distillation tower. An example is given in Figure 3.56. The vapor (PC1) and liquid (LC1 and LC3) inventories are controlled. The top product composition (AC2) is controlled by adjusting the reflux flow rate, and the bottom product composition (AC1) is controlled by adjusting the flow of steam to the reboiler. The design in Figure 3.56 is just one of many possible, with variations depending on the physical properties of the fluids, operating conditions, economics, and operating window. Please see the references given above for other designs.

3.5.3 Refrigeration

Cold temperatures are required for condensation (at reasonable pressures), food processing, materials processing, and many other processes. Ultimately, heat is exhausted at ambient temperature, so various refrigeration processes are employed to effect cooling below ambient temperatures. In this sub-section, flexibility and control is discussed for a closed cycle, vapor recompression refrigeration system that involves four stages; compression, condensation, throttling, and evaporation. The key feature of this process is compression of the vaporized refrigerant, which raises the refrigerant temperature above cooling water temperature. After compression, the refrigerant can be condensed at the higher temperature and

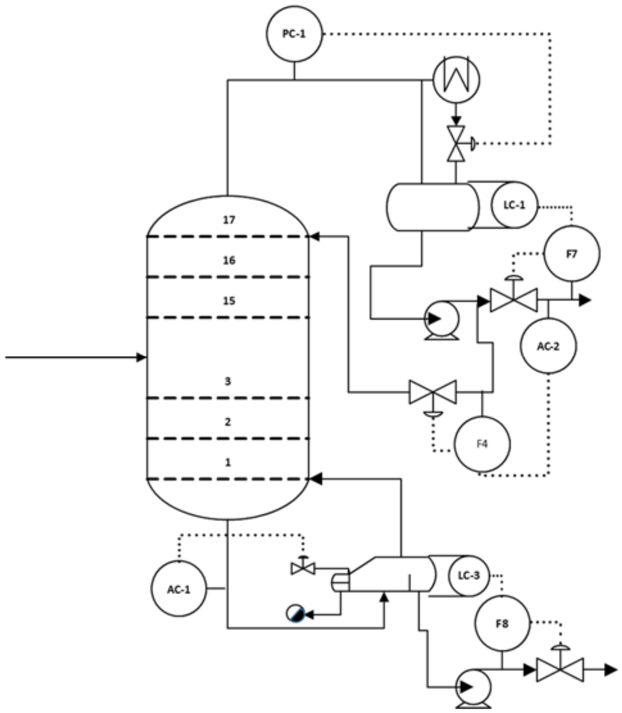


Figure 3.56. Typical two-product distillation control

pressure using cooling water, before flowing to a lower pressure through a throttling valve where it is vaporized at a temperature below ambient temperature.

A vapor recompression refrigeration system with one compressor and numerous consumers is shown in Figure 3.57. Each of the consumers decides its refrigeration requirements independently for temperature or pressure control of its own process. The refrigeration system is required to satisfy these demands completely and without delay. Therefore, this is a "pull" system for supplying refrigeration.

Clearly, flexibility must exist for each consumer to achieve its own objectives by adjusting the flow of refrigerant; this is achieved by providing a separate valve for each consumer. The flow to the consumer should be immediately available, which is achieved by an inventory of refrigerant in the storage drum. Note that the level in this drum cannot be controlled because the refrigerant is in a closed circuit, so that any flow leaving the drum will return in a short time. Naturally, piping (not shown in the diagram) is required for initial filling, draining for maintenance and small purge, if required.

The vapor is collected from all of the consumers without the need for control valves; any valves would introduce unnecessary pressure drops and increase the power required by the compressor. The vapor inventory is regulated by measuring and controlling the compressor suction pressure. In the design, the pressure controller adjusts the speed of the rotation of the compressor in a cascade control strategy, and the speed controller manipulates the steam flow to the turbine. While only one stage of compression is shown in the figure, several stages are typical and would not fundamentally change the design shown. The high-pressure vapor is cooled and condensed in a heat exchanger using cooling water from a cooling tower. The flow of water is not regulated by a control valve; the maximum flow is desired at all times.

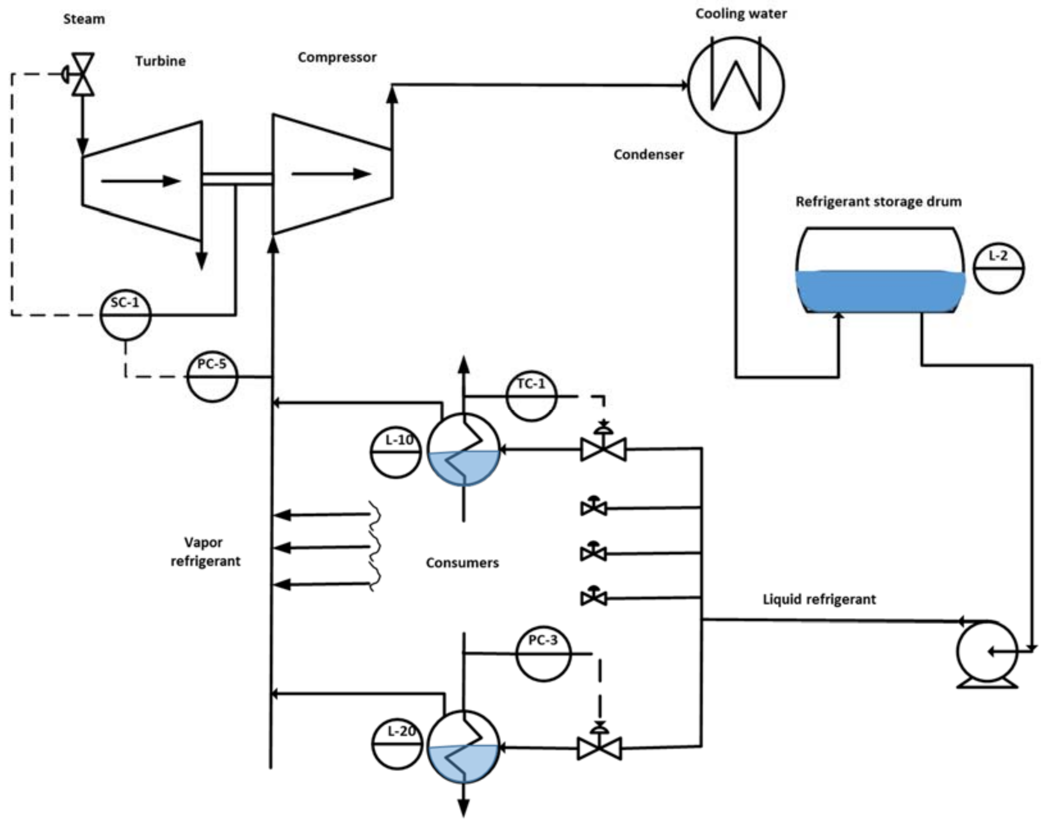


Figure 3.57. Vapor recompression refrigeration system with flexibility and control.

3.6 Flexibility Requiring System Changes

Most of the flexibility approaches presented in previous sections enable a person or control system to adjust manipulated variables immediately and with fine resolution, i.e., small incremental changes over a wide range. This is desirable for responding quickly and appropriately to process variability. In this section, flexibility approaches are presented that require manual actions, cannot be implemented quickly, and might require considerable time and/or a temporary process shutdown.

3.6.1 Flexibility by adjusting equipment in service.

All equipment has an acceptable range of operation determined by its capacity and turndown ratio. Process flexibility (and operating window) can be increased by installing parallel equipment and operating only the equipment required for the current production capacity. A few examples are given in the following.

- Parallel pumps – For example, two pumps in parallel can provide nearly twice the total flow rate as one pump, while the minimum sustainable flow rate with one pump in operation is reduced by one half.
- Cooling tower cells – The desired cooling water return temperature can be achieved with fewer than the maximum number of cells/fans in operation. Therefore, the cooling tower operation can be adjusted to match the demands from the process.
- Boilers – A typical plant has several parallel boilers; one major reason is reliability. Since several are available, the number in operation can be adjusted to match the steam demand from the plant. This flexibility increases the turndown ratio for the total steam generation (as well as increasing the efficiency of the entire system).

These approaches can be included in the original design to accommodate anticipated variability.

3.6.2 Flexibility through equipment modifications

Plant design is performed based on predictions about future raw material availability, product demands, energy costs, and so forth. Sometimes, important factors change between design and operation, and engineers need to modify equipment so that it provides efficient operation for unanticipated conditions. A few examples of modifications that require some or all equipment to be modified are given in the following.

- Pump impeller – When the new operation is far from the pump best efficiency point (BEP), the impeller can be replaced with an impeller that is smaller to match the lower required flow rate or larger to match the higher required flow rate. This flexibility requires that the original pump be specified with a casing that can accommodate an impeller at least one size larger than originally installed.
- Tray modifications – Operation at lower production rates can lead to inefficient tray contacting due to weeping. One method for improving operation is to "blank" some of the tray active area where weeping can occur. An advantage of this approach to increasing flexibility is that it is reversible because the blanking can be removed when the production rate increases.
- Steam balance – If excess steam is available due to heat integration, a turbine can be installed to generate electricity. This generation can be adjusted to use all excess steam without affecting plant production rate.

These approaches will typically not be included in an original design and will be employed only when unanticipated variability occurs.

3.7 Conclusions – Wrap-up and Lookahead

As we have seen, the operating window and flexibility are closely related concepts. When designing for the operating window, the engineer ensures that the process equipment has the capacity to achieve the desired operating window taking into account the expected disturbances and changes to the production rate and product specifications. While performing this analysis, adjustable manipulated variables must be selected. Subsequent to the operating window analysis, flexibility must be added, so that the desired operating point can be achieved. While some of the flexibility designs are straightforward, like adding valves for flow control, others have introduced rather novel methods for adjusting process behavior, like adding by-passes around heat exchangers and changing the area for heat transfer in flooded condensers. The culmination of the flexibility design provides production control of integrated units.

In the next two chapters, additional design objectives are introduced, along with approaches for achieving these objectives. In Chapter 4, reliability is addressed to enhance designs with equipment specifications, process structures and control systems that improve economic performance. In Chapter 5, safety is addressed through the "control for safety" hierarchy and analysis methods that significantly reduce the likelihood of hazards to workers. In Chapter 6, process control methods are introduced to automate many of the flexibility, reliability and safety objectives.

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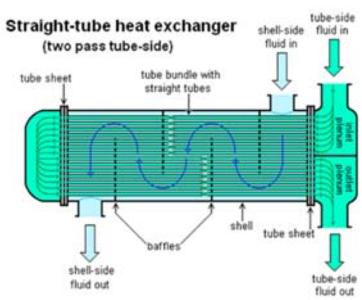
Test Your Learning

1. Discuss how you would add flexibility and flow control for a positive displacement pump with a constant speed driver. Include a sketch in your answer.

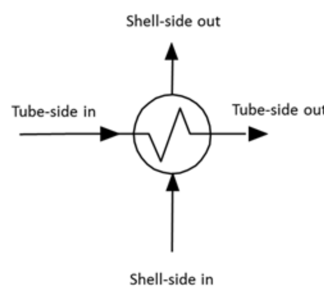
2. Flexibility and control for a compressor was discussed in Example 3.6, which introduced a recycle for anti-surge control. How would you determine the best set point for FC-2 for the following two situations?
a. A constant set point input once for operation over a long period of time, potentially years.
b. A FC-2 set point that is calculated continuously using real-time measurements. You may add sensors to support your answer.

3. The flexibility design for a simple blending process is given in the solution for Example 3.1.
a. Explain the reason why each component system has two valves.
b. Design a control system that achieves the objectives defined in part a.

4. For the shell and tube heat exchanger in Figure Q3,4, design flexibility and a control system to control the outlet temperatures of both streams. You may add piping, sensors and valves in your solution.



a. Exchanger schematic, Padleckas (2006)



b. Piping and instrumentation symbol

Figure Q3.4 Shell and tube heat exchanger

5. Design a feedback control strategy for the jacketed heat exchanger in Figure3.28a. Your design should automatically provide cooling or heating as needed without simultaneous heating and cooling, which would be wasteful.

6. A basic feedback control strategy for a fired heater is shown in Figure 3.29.
a. Enhance your design with feedforward where necessary.
b. Enhance your design further by applying the firing controls approach explained in the boiler flexibility section.

7. The location of spill tanks for intermediate products (work in progress) allows for short-term differences between sequential units that must process the same *average* amount of material. Often, the tanks have temperature limits that require cooling before sending fluid to the tank and subsequent heating when stored material is send to the downstream unit. This cooling and heating increasing operating cost, so the amount of material diverted through the spill tank should be minimized. Design a control system to control the last level in the upstream process, the flow rate to the downstream process, and minimize flows to and from the spill tank.

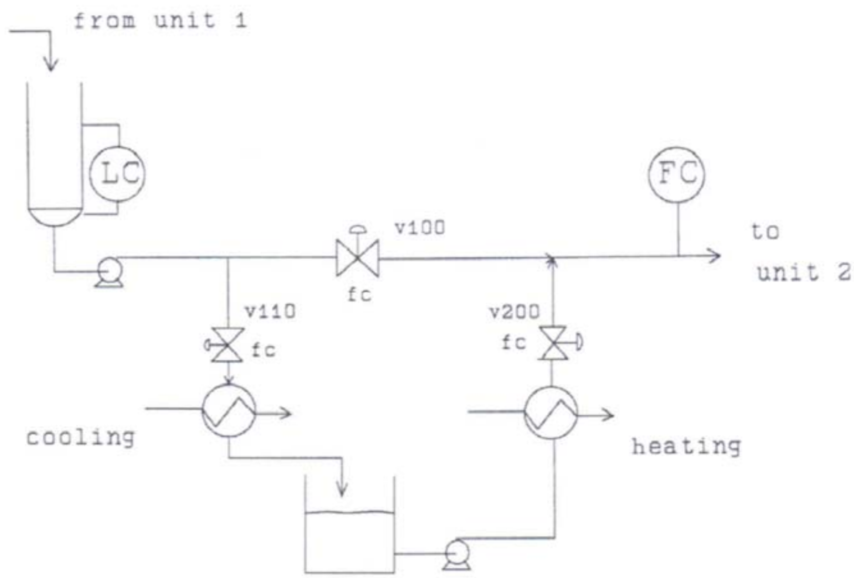


Figure Q3.7

8. Refrigeration can be employed to cool a separate fluid that can be provided to numerous consumers distributed over large distances. For example, a centralized refrigeration unit can cool water that can be used to provide air conditioning in an entire building or even many buildings on a campus. This type of centralized refrigeration is often purchased as a "chiller", which is a packaged system designed and fabricated by a vendor company. A picture of a chiller is shown in Figure Q3.8a, and a schematic of the system is shown in Figure Q3.8b. Design the equipment flexibility, automatic process control, and manual adjustments required for this system to perform well. Your answer should also address the cooling tower.

Figure Q3.8a.

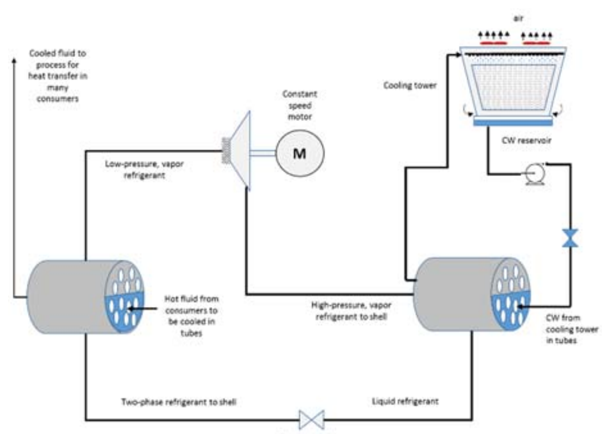


Figure Q3.8b.

9. Flexibility and control for a simple two-product distillation tower is presented in the chapter. Develop answers for the following extensions and include a sketch in your solution.

a. Design flexibility into a column bottoms with a pumped reboiler.
b. Investigate equipment used for vacuum distillation and design flexibility for the overhead system, including the condenser.

c. Investigate the design for a two-product tower with vapor-compression. Add flexibility and controls for your design.

10 . A hot oil circuit with two levels is shown in Figure Q3.10. The process in the figure includes a fired heater, chemical reactor and heat exchangers to recover energy by heat transfer to other processes in the plant. The goals are in descending order;
1) to have tight flow control (Fl),
2) tight control of the reactor outlet temperature (T2),
3) good control of temperatures T3, T4, T7 and T8 in the integrated processes, and
4) maximum heat recovery at the highest temperature possible.

The sensors and manipulated variables are shown in the figure. Disturbances are set point changes to the process flow and changes in the heating requirements of the heat-integrated processes.

a. Without changing the instrumentation and process equipment, design a control system to achieve the objectives, if possible.
b. By making the minimum changes to the process and instrumentation, design a system which improves on the result in (a).

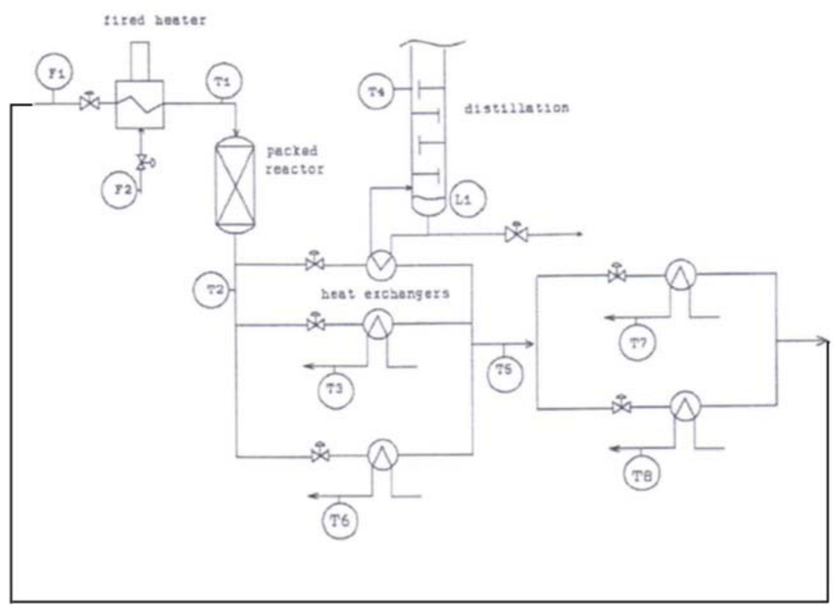


Figure Q3.10

11. Proper operation of the fuel gas recovery and distribution system is essential for a process plant. A typical system is shown in Figure Q3.11. Several processes in the plant produce gas, and this control strategy is not allowed to interfere with these units. Also, several processes consume gas, and the rate of consumption of only one of the processes, Consumer 2, may be manipulated by the control system. The flows from producers and to consumers can change rapidly and over a large range. Extra fuel gas sources are provided by the purchase of fuel gas and vaporizer, and an extra consumer is provided by the flare. (Flaring by-products, in addition to being wasteful, can lead to fines from the government.) The relative dynamics, costs and range of manipulation are summarized in the following table.

flow	manipulated	dynamics	range (% of total flow)	cost
producing	no	fast	0-100%	n/a
consuming	only one flow	fast	0-20%	very low
generation	yes		0-100%	low
purchase	yes		0-100%	medium
disposal	yes		0-100%	high

a. Complete the blank elements in the table based on your knowledge of equipment behavior.
b. Design a control strategy to satisfy the objectives. You may add flexibility by adding only sensors and final elements as required.
c. Suggest process equipment change(s) to improve the performance of the system and modify your control system in part b to accommodate your equipment changes.

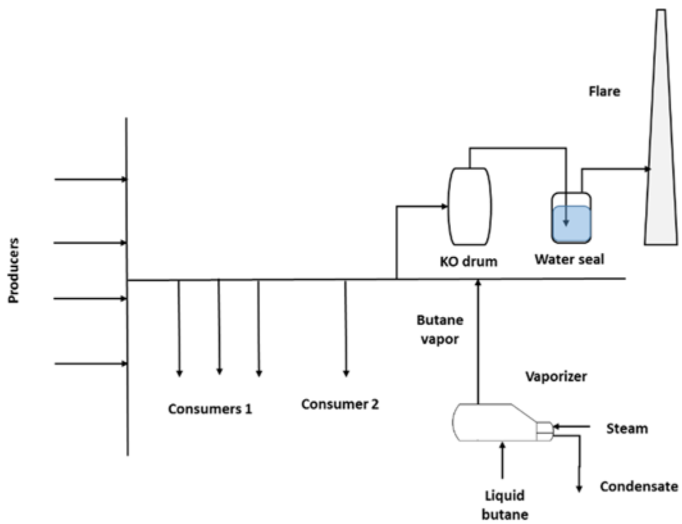


Figure Q3.11.

12. A process flow diagram for a naphtha reforming process that increases the octane of a distillation cut for use in gasoline is shown in Figure Q3.12. Add flexibility with sensors and final elements and design a production control system. Is your design a “push” or “pull” system?

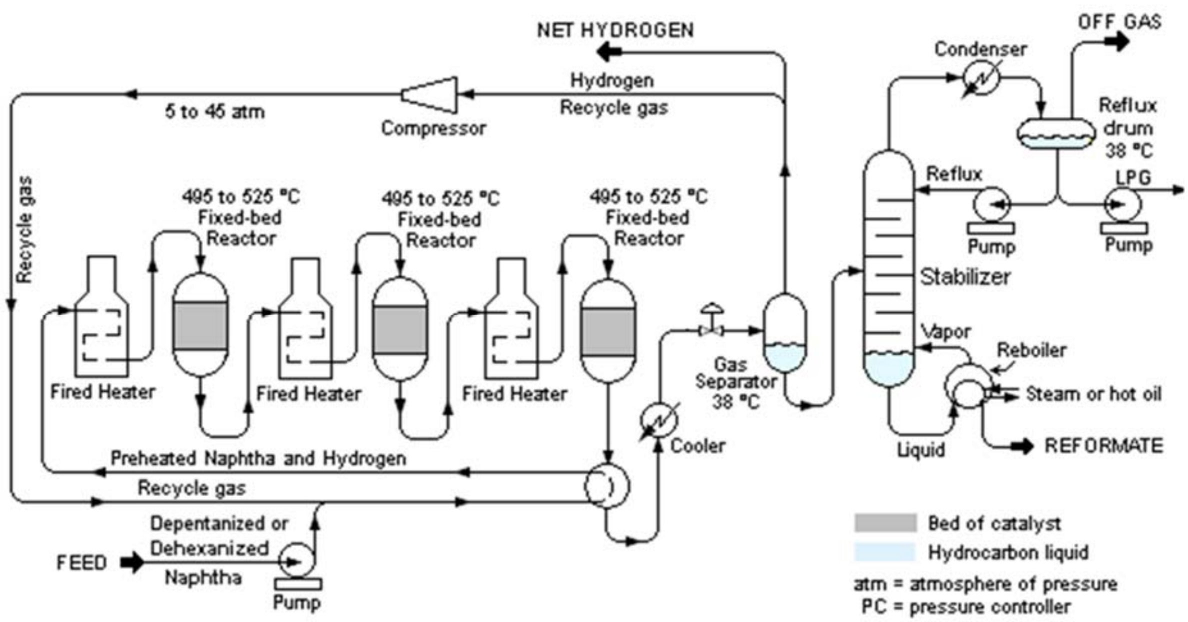


Figure Q3.12. (Mbeychok, 2007B)

13. A process flow diagram for a recovery process separating a component A from an inert component is shown in Figure Q3.13. Add flexibility with sensors and final elements and design a production control system. Is your design a “push” or “pull” system?

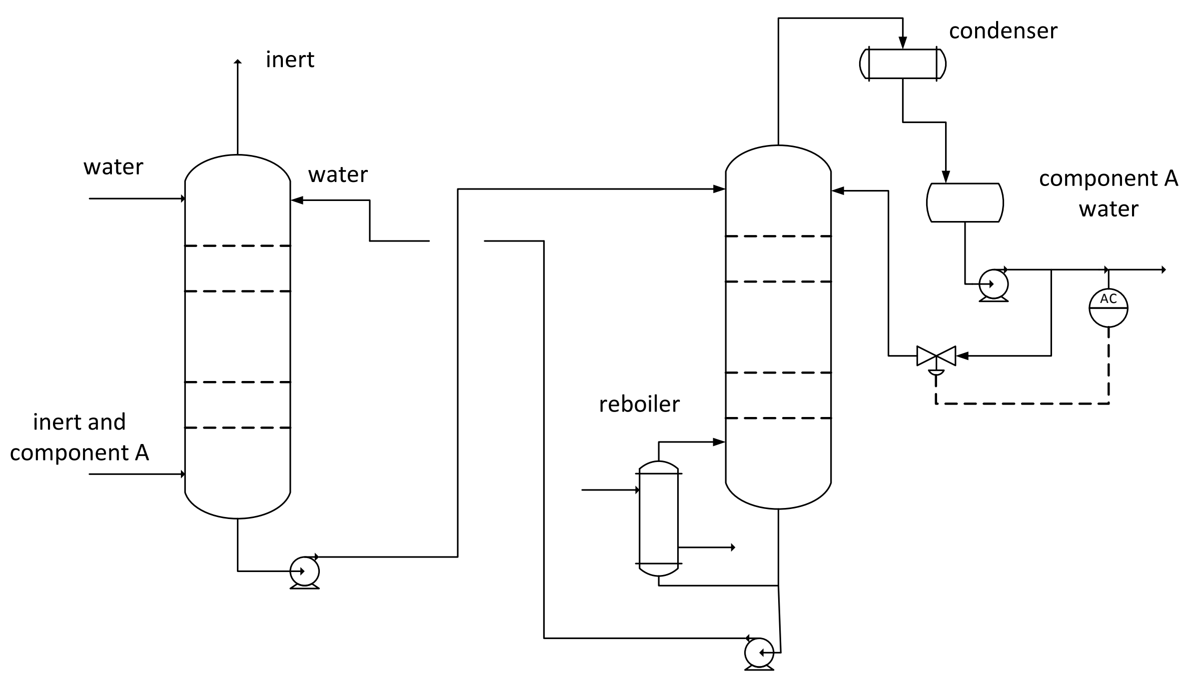


Figure Q3.13

14. The first process in a petroleum refinery is an atmospheric distillation unit that separates crude oil into numerous intermediate products for further processing. For the process in Figure Q3.14, add flexibility

with sensors and final elements and design a production control system. Is your design a "push" or "pull" system?

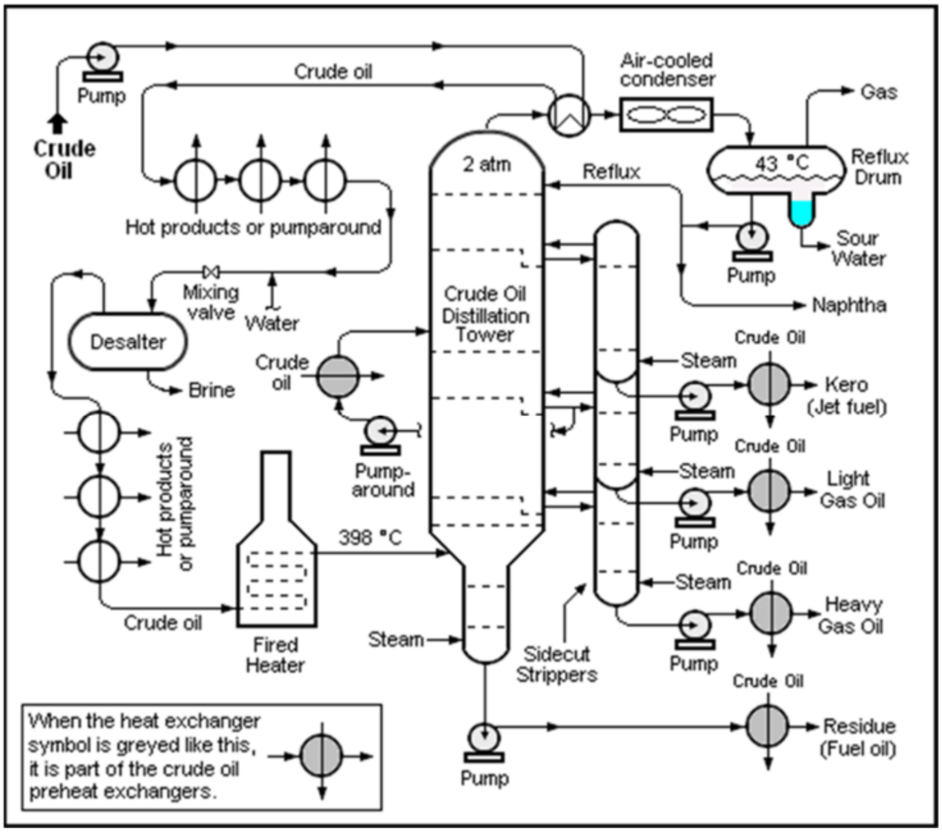


Figure Q3.14 (Mbeychok, 2006)

15. The heat exchanger network in Figure Q3.15 was analyzed in Chapter 2 for its operating window. Enhance the design to include flexibility to achieve the window evaluated in Chapter 2.

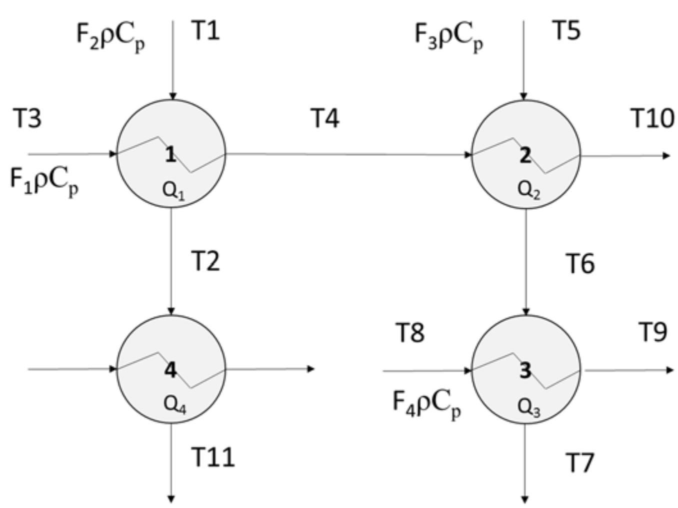
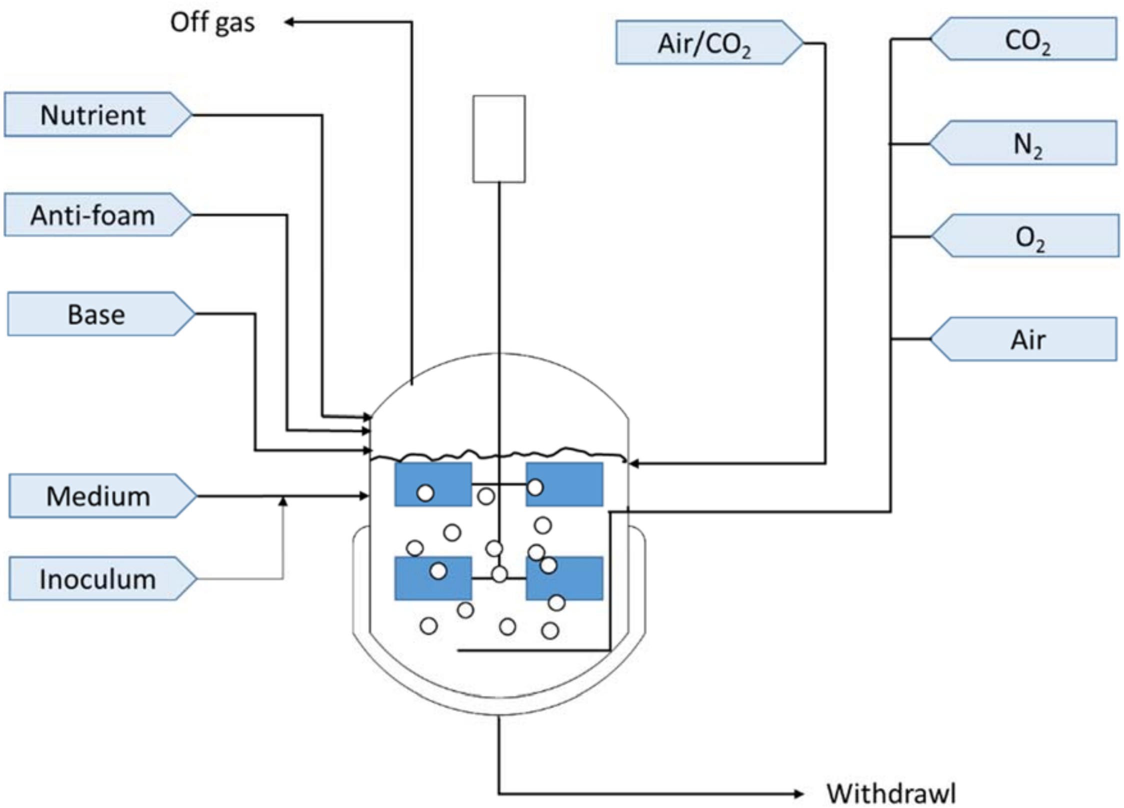


Figure Q3.15

16. A steam system with flexibility and some regulatory controllers is given in Figure 3.49. Enhance the control design by including adjustments in the letdown valves v100, v200, and v300. The goals are to prevent high and low pressures in the headers (distribution pipes) at all three levels and to minimize flows through the letdown valves.

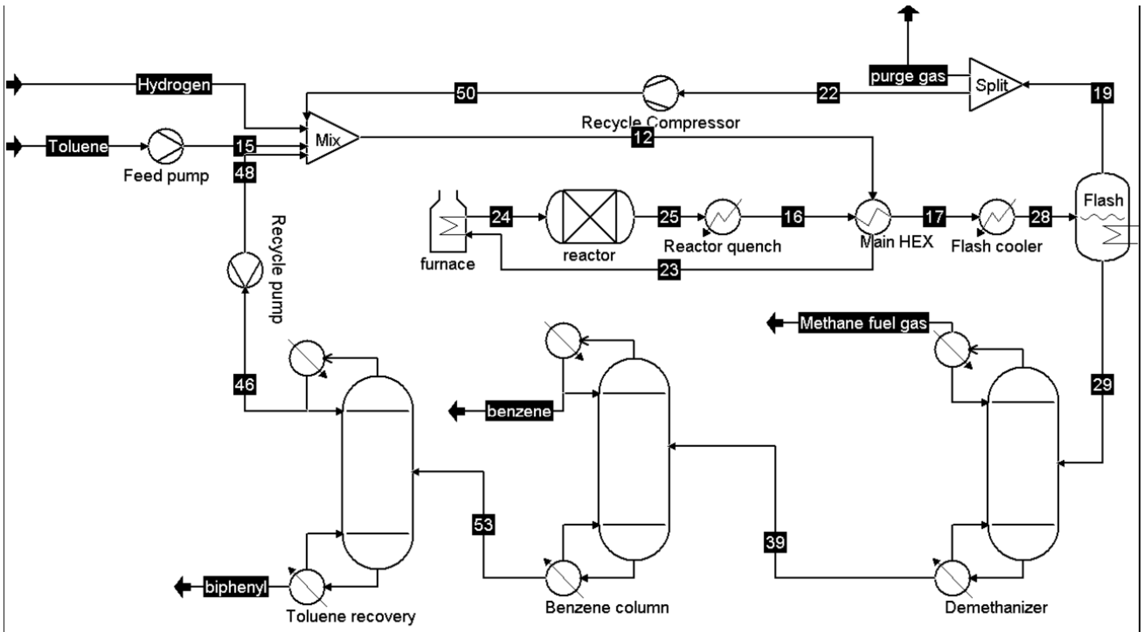
3.17 A sketch of an animal cell culture batch reactor is given in Figure Q3.17. Many streams are needed during the batch, some continuously, some for short duration and some only in exceptional circumstances. Add flexibility, sensors and control systems for good operability of this reactor.



Q3.17 (After Julien, C. and W. Whitford (2007))

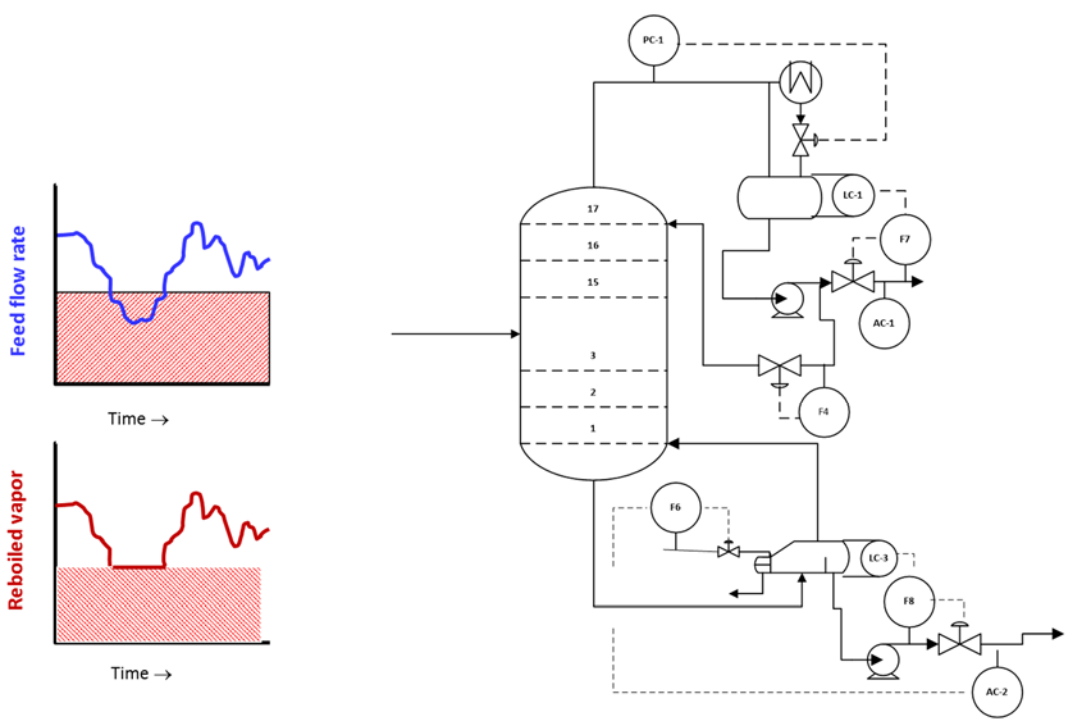
18. A classic process design problem is the dealkylation of toluene to benzene with hydrogen. For the process in Figure Q3.17, add flexibility with sensors and final elements and design a production control system. Is your design a “push” or “pull” system?

19. In Chapter 2 on the Operating Window a distillation tower was analyzed in Example 2.3, where the operation was limited by the turndown at low feed rates. When the reboiler duty was reduced in response to the lower feed rate, weeping is predicted to occur on the trays. The desired behavior is shown in Figure Q3.19a. The original control system is shown in Figure Q3.19b; modify the control system to achieve the desired behavior.



Stream	Hydrogen	Toluene	purge gas	Methane fuel gas	benzene	biphenyl	Unit
Pressure	38.3	1	32.8	10	1	1	bar
Temperature	38	25	38	38.6688	79.7269	241.369	°C
Flow rate	909.978	15387.5	3287.95	196.091	12392.5	421.018	kg / h
Mass frac Hydrogen	0.7	0	0.0926999	0.00832077	0	0	
Mass frac Methane	0.3	0	0.844697	0.865015	0	0	
Mass frac Benzene	0	0	0.0552264	0.126654	0.999938	3.27013e-11	
Mass frac Toluene	0	1	0.00737562	1.01007e-05	6.23028e-05	0.0117736	
Mass frac Biphenyl	0	0	1.59434e-06	0	0	0.988226	

Figure Q3.18 (Anon, 2019)



a. Desired behavior

b. Process schematic with original control design

Figure Q3.19 Distillation tower with lower limit on reboiler duty from Example 3.2 in Chapter 2