Process Instrumentation

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1. General concepts of process control systems

1.1. Elements of process control systems

A successful operation of chemical plants depends on the following requirements - *safety, production specifications, environmental regulations, operational constraints,* and *economical*. There are many types of processes and processing equipment (absorbers, heat exchangers, dryers, separators, reactors, distillation columns, pumps, etc). They are connected together to reach the objectives of the plant - *to produce a desired product from the stock using the most safety and economical procedures*. Therefore, we must be able at all times control all process parameters and all operations of a plant. We can solve this problem by using *a control system*, which consists of *measuring devices, controllers, valves, computers, transmission lines and intervention of plant personnel*.

Objectives of every control system are as follows:

1) to suppress the influence of external disturbances, i.e. the effect of surroundings on the process;

2) to ensure the stability of a chemical process, i.e. to keep process parameters (variables) as close as possible to their desired values;

3) to optimise the performance of a chemical process, i.e. to meet the requirements of safety, satisfaction of production specification and maximising of economic objectives.

Let's consider two systems for the control of temperature and level of liquid in a stirred tank shown in **Fig. 1.1**. These two control systems have all elements inherent to every control system, namely:

1) a *process* - the stirred tank;
2) *controlled variables* - temperature of the effluent liquid (or temperature of the liquid in the tank) and level of the liquid in the tank;
3) a *transducer*, a *measuring instrument*, a *transmitter*;
4) a *transmission line* (electrical, pneumatic or hydraulic) that carries a measurement signal from a measuring instrument (or transducer) to a controller;
5) a *control signal* from a controller to a final control element (for example, a control valve);
6) a *controlling device* or a controller;
7) a *final control element* - a control valve.

In **Fig. 1.1** we used the following symbols and abbreviations:

CV - a control valve.
F_{in}, F_{out}, F_{st} - flowrates of inlet and outlet streams of the liquid, and steam, respectively;

H_s - a desired value (set point) of the liquid level in the stirred tank;
LT - a level transmitter;
TE - a thermocouple;
T_{in}, T_{out}, T_{st} - temperatures of inlet and outlet streams of the liquid, and steam, respectively;
T_s - a desired value (set point) of the temperature in the stirred tank.

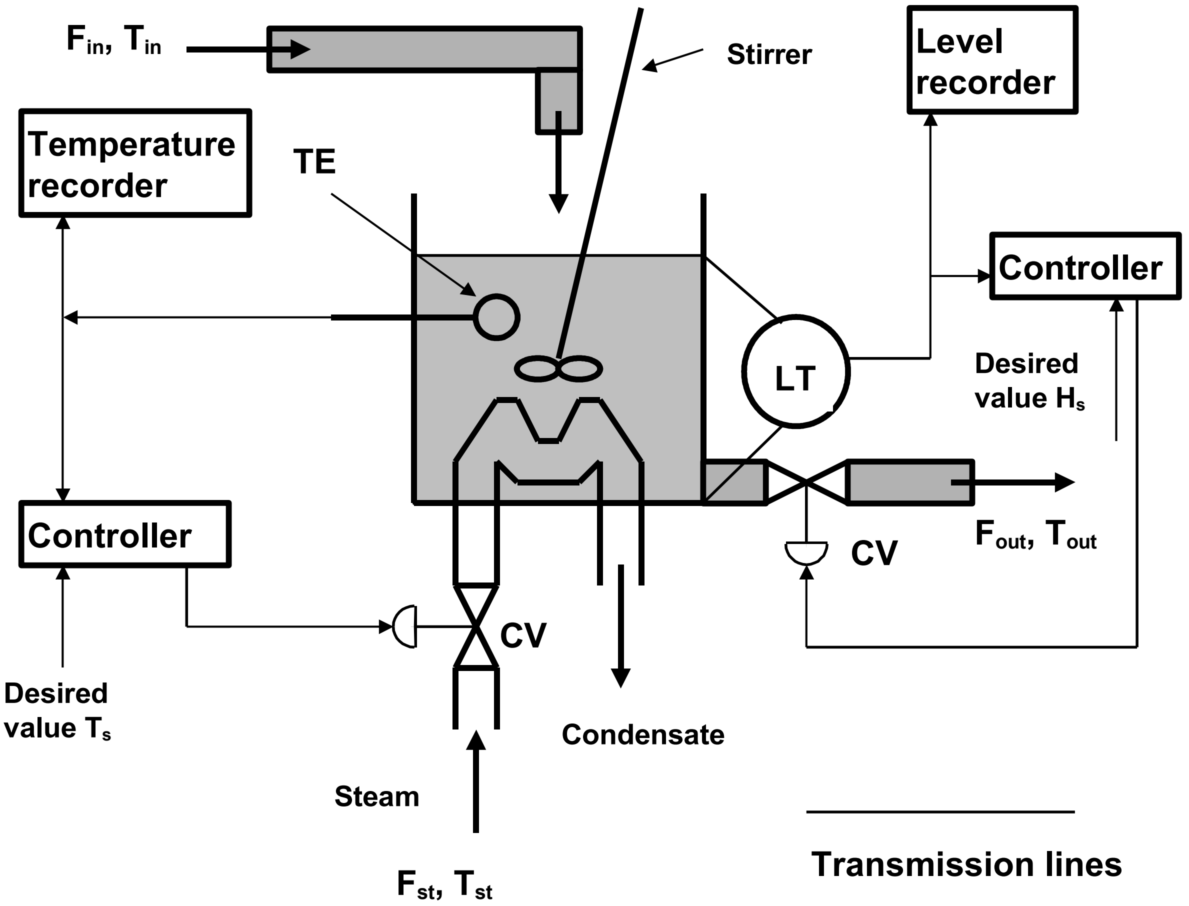


Figure 1.1. Process control systems for a stirred tank.

A *process* is an equipment or apparatus for which supply of energy, material, etc., and demand must be balanced. We don't include in this concept control hardware. There are many types of processes: from simple, such as our example or a tank for storage of liquid hydrocarbons, where liquid level should be kept within an acceptable range, to complex processes such as distillation columns and reactors.

A *process variable* is a physical or chemical property, quantity or other condition which can be changed. Here are several examples of process variables: a *flow rate* of a feed stream into a distillation column; a *pressure* of gas in a storage tank; a *level* in a condenser; a *temperature* of a liquid stream (feed to a reactor) exiting from a furnace; *pH* of a solution in a stirred tank; *density* and *viscosity* of liquid products of oil refining (these parameters are usually used as an indicator of desirable quality of products); a *resistance* of an electrical circuit; a *speed* of rotor revolution, etc.

In general, process variables can be classified as shown in **Fig. 1.2.** Now we can give explanations of types of process variables with the examples from **Fig.1.1.**

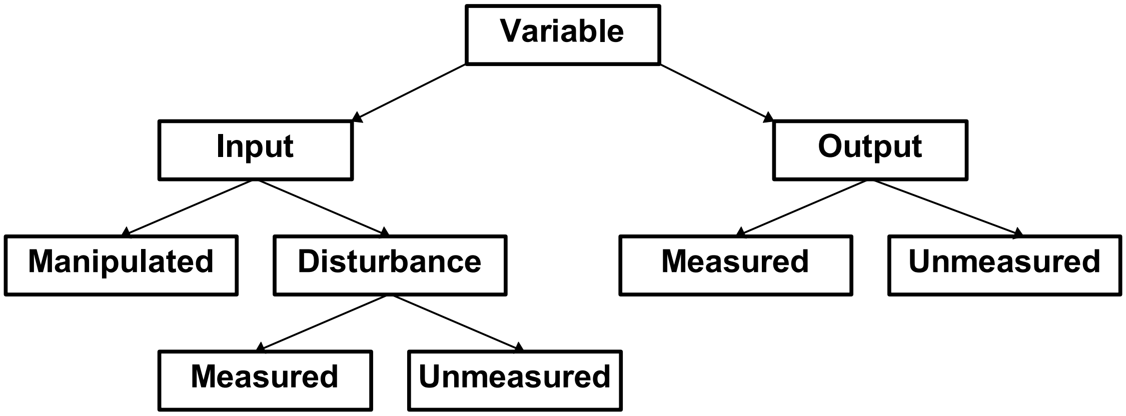


Figure 1.2. Classification of process variables.

Input variables reflect the effect of the surroundings on the process ($F_{in}, T_{in}, F_{st}, T_{st}$).

Output variables denotes the effect of the process on the surroundings (F_{out}, T_{out}, H).

Manipulated variables can be adjusted freely by the human operator or a controller (F_{st}, F_{out}).

Disturbances are not the result of an adjustment by an operator or a controller(F_{in}, T_{in}, T_{st}).

Measured variables - their values can be directly measured by a measuring device ($F_{in}, T_{in}, T_{out}, H$).

Unmeasured variables - their values are not or cannot be measured directly (in chemical processes - the feed composition for a distillation column).

A *transducer* is a device which can convert information of one physical form to another type of its output (for example, *resistance temperature detector* converts the change of the measured temperature into the change of the electrical resistance of a metal conductor).

A *measuring instrument* is an element which senses, detects or converts the above mentioned physical parameter or condition into a form or language that a person (an operator) or controller can understand.

Examples:

⑤a manometer converts the change of pressure into the movement of an arrow along a scale of an instrument;
⑤a mercury-in-glass thermometer converts the change of temperature into the change of the length of a mercury column.

A *transmitter* is a device that converts a process variable into a form of a signal suitable for transmission to another location. Temperature is detected by a temperature transmitter, then it is converted to an analog electrical (*4-20 mA, 0-5 mA, 0-20 mA, 0-10 V, 0-5 V, -10 to +10 V, -5 to +5 V dc*), or pneumatic (*20-100 kPa*), or digital signal which is proportional to the temperature under measurement. This signal is sent to a controller. A measuring instrument or transducer must be capable faithfully and accurately detect any changes that occur with the measured process parameter.

Transmission lines are used for carrying a measurement signal from a measuring instrument or transmitter to a controller, and from a controller to a final control element (control valve, for example). Very often these lines are equipped with amplifiers to increase the measurement signal, since it is very weak (for example, a thermal electromotive force of a thermocouple has the magnitude of several dosens of millivolts).

A *controller* is an element that compares a current value of a controlled variable (the input variable for a controller) with a desired value (the set point) and takes appropriate control actions to adjust values of manipulated variables in the way to reach the desired value of process variable. In our example (see **Fig.1.1**) the controller changes flowrates of steam entering the heat exchanger and effluent liquid.

As the result of this action, the process variable (the temperature of the liquid in the outlet of the stirred tank in **Fig. 1.1**) changes in such a way, that it approaches closer to the desired value (set-point). This is a *closed-loop* or a *feed-back control system*. Feedback is an information about the status (or the magnitude) of the controlled variable which can be compared with its desired value. A control system without feed-back is called an *open-loop control system*. In other words, if we remove the temperature transducer and level transmitter, controllers and control valves, or simply brake links between thermocouple and level transmitter and controllers, or between controllers and control valves (see **Fig.1.1**) and leave the tank not under control we will get an open-loop or unregulated system. In this case information about controlled variables (the temperature and level of the liquid in the tank) is not used for control of these process variables.

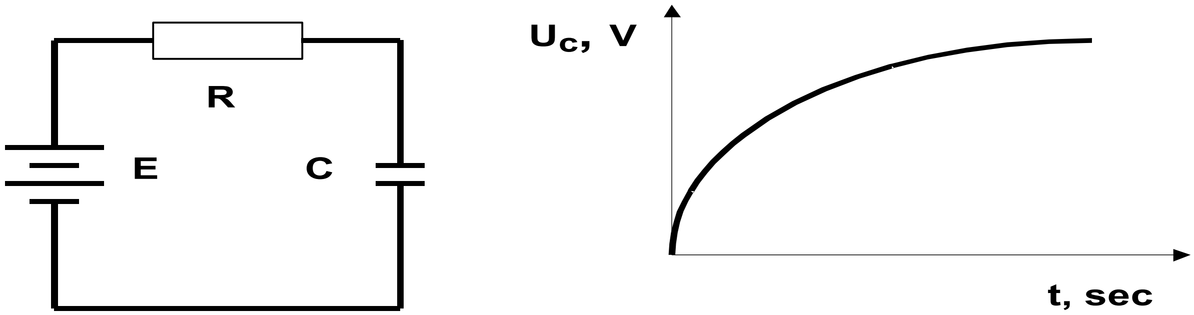
It is interesting to note that an unregulated system can be *selfregulated*. Assume that the flowrate of the inlet liquid suddenly has increased to another value. Since $F_{in} > F_{out}$, the liquid will be accumulated in the tank (the level will increase). Thus increased liquid level will inevitably increase the head of the liquid, which in its turn will increase the value of F_{out}. This will continue until that moment when $F_{in} = F_{out}$. After that, the level will be maintained on another value.

A *final control element* is a device which receives the control signal from a controller and changes the amount of matter or energy entering the process in a way to bring the controlled variable (process variable) to its set point. As examples, we can mention control valves, relay switches providing on-off control, variable-speed pumps, etc.

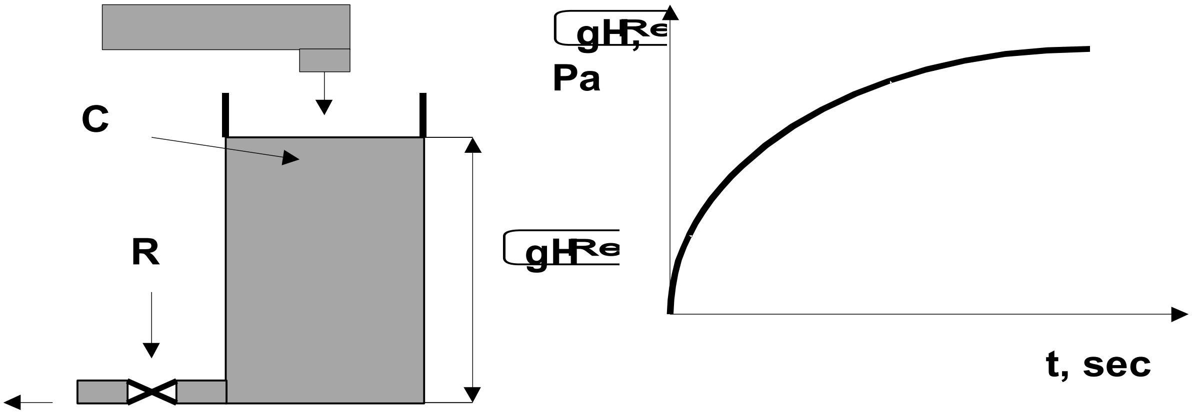
1.2. Types of processes

All physical systems can be categorised in terms of types of energy used in it. Let's consider the most common of them: electrical, hydraulic, pneumatic and thermal (see **Figure 1.3)**. Generally speaking, a system can be of any physical type. Common among all these types of physical systems is that each has a single capacity and a single resistance. How these systems behave in respect to time?

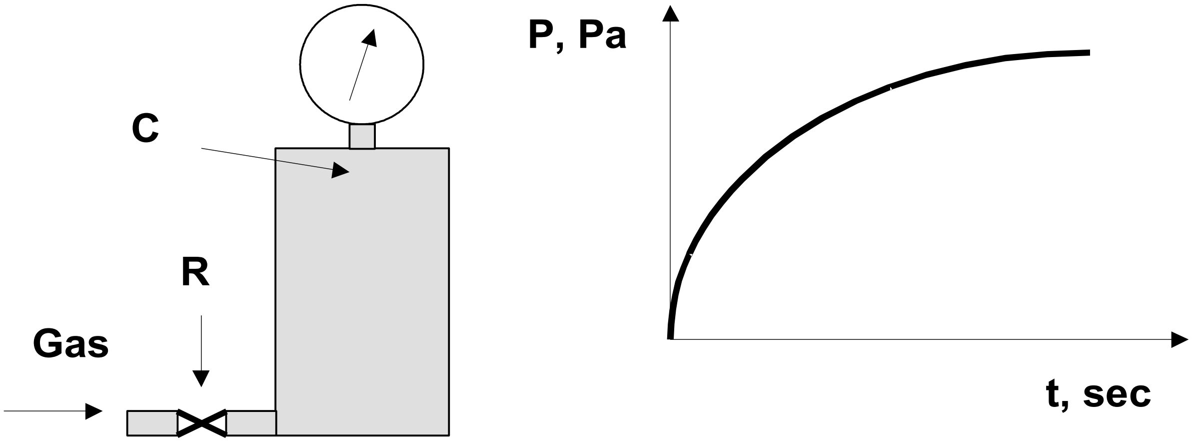
Let's examine behaviour of an electrical system shown in **Fig.1.3a**. Suppose that the circuit is closed and the capacitor starts to charge to the voltage of the battery. Thus we imposed a *step upset* or *step change* (a change from one level to another in supposedly zero time) in the input of the system. Now we start examine how the output of the system (voltage of the capacitor) changes with respect to time. Then, if we measure values of a voltage of the capasitor U_c at various times and plot them vs time, we'll get the curve shown in **Fig.1.3a**. To get more accurate picture we present this curve in the scale (see **Fig. 1.4**).



a - electrical

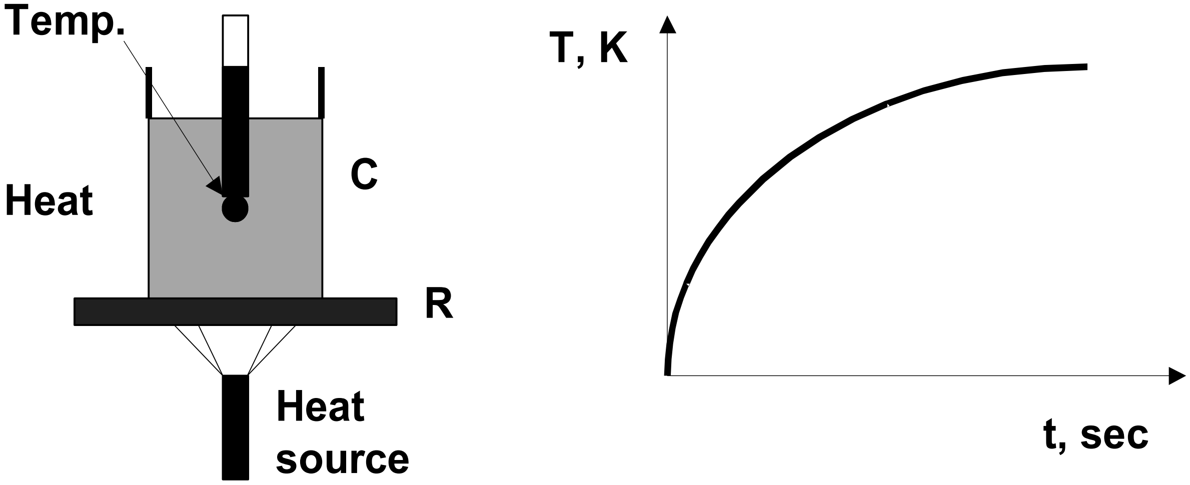


b - hydraulic



c – pneumatic

Figure 1.3. Types of physical systems and their reaction (response) curves.



d - thermal

Figure 1.3. (continued) Types of physical systems and their reaction (response) curves.

As the voltage of the capacitor approaches to the voltage of the battery (corresponds to 100%) the charging rate gradually decreases. It was noted that a *time interval* necessary for the capacitor to charge to the 63.2% of the battery voltage (no matter what is the battery voltage) is *constant* for any one value of the resistance (R) and the capacitance (C). This time is called the *time constant*. To get the value of the time constant we must multiply the values of resistance and capacitance:

$$\tau = R * C, \qquad \textbf{(1.1)}$$

where: τ - time constant, *s*.

The unit for the time constant is *second*. In the case presented in **Fig.1.4** the time constant is equal 20 sec. It means - the voltage of the capacitor will be equal to 63.2% of the battery voltage after 20 sec will have passed from the beginning of a charging process. For example, if the battery voltage is equal to $U_B = 50, V$, then after 20 sec the voltage of the capacitor will be equal to $U_C = 31.6, V$.

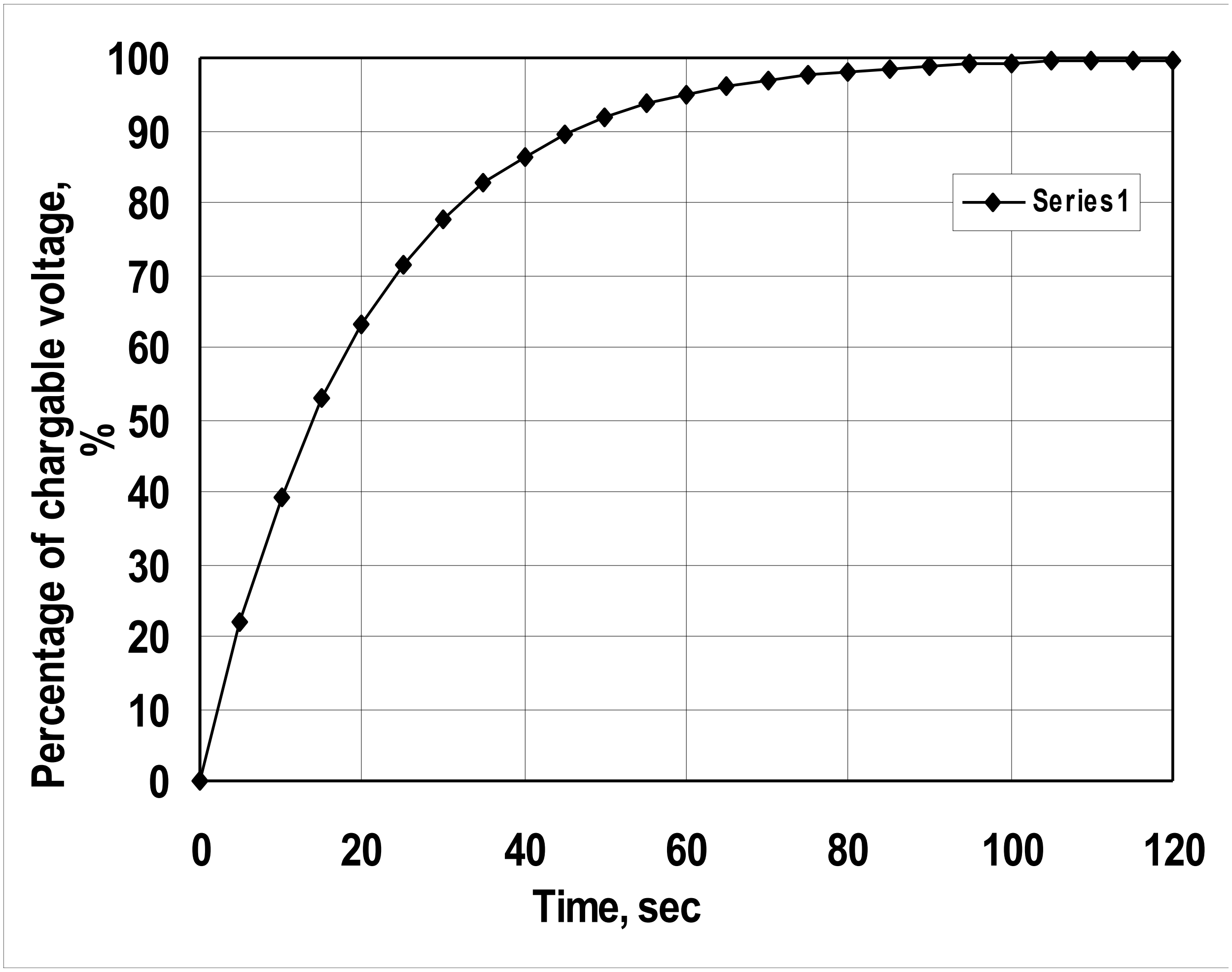


Figure 1.4. Response curve.

The process examined in this case is called *transient process*. The curve in **Fig. 1.4** is called a *reaction curve*. The form of this curve is *exponential*, and sometimes the curve is called *exponential-transient curve***.** The capacitor never will charge to the same voltage as the battery, but after t [illegible] 4.6[illegible] seconds the former will charge to 99% of the battery voltage. This time we can accept as the end of the transient process.

What is common regarding to response curves of all types of physical processes presented in **Fig. 1.4** is that they all have exponential character.

Dynamic characteristic of a system defines behaviour of a process in respect to time (see **Fig. 1.3** and **Fig. 1.4**).

<u>*Static characteristic*</u> of a system defines behaviour of a process which does not involve time or which takes place over a sufficient length of time that dynamic changes become of minor importance. Static characteristics can be of linear and non-linear character.

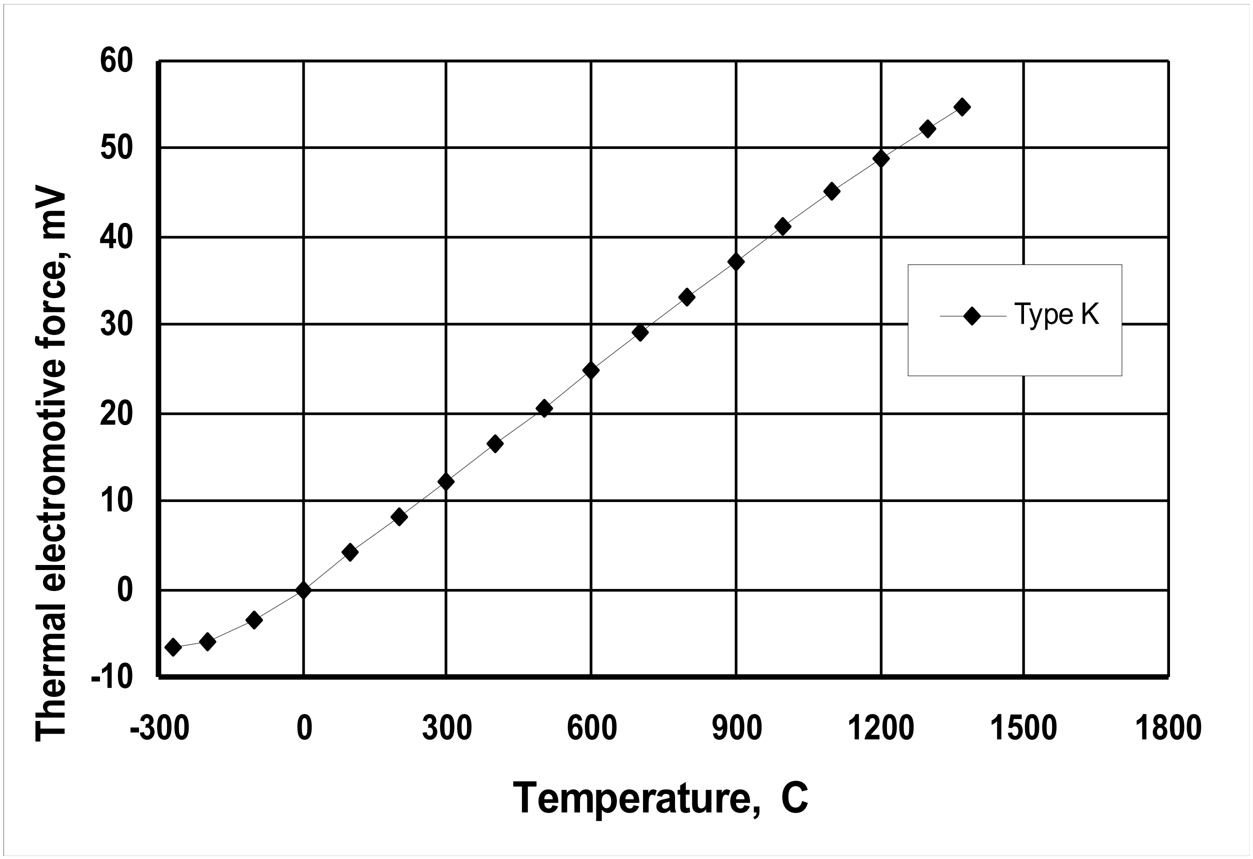


Figure 1.5. Static characteristic of a thermocouple of Type K.

At temperatures from -300 to 0 °C a static characteristic of a thermocouple (see **Fig. 1.5**) has non-linear character, whereas at temperatures above 0 °C it is close to linear one.

1.3. Elements of metrology in measurements of process variables

As we mentioned above, the more accurate a measuring instrument can measure the value of a process variable the more <u>*accurate*</u> a control system can control this variable. As a result, we can achieve the objective of a particular process (the desired quality of the product, the minimum consumption of energy, etc). What do we mean under the term of an <u>*accuracy*</u>?

<u>*It is not possible to measure any variable without an error.*</u>

An *error* of the measurement is the difference between a measured value and a true value of a measured variable. Since we cannot determine the true value of a measured variable then, instead of it, we can use its actual value, which can be measured by a reference measuring instrument with a high degree of accuracy. Thus, an *absolute* *error* is equal to the absolute value of the difference between a measured value and an actual value of a process variable, as follows:

$$A = \left|A_m - A_a\right|, \tag{1.2}$$

where: A_m - the value determined by a measuring device;

A_a - the actual value of a process variable.

This error is expressed by the units of the measured variable (or quantity), ie, m, A, V, m/s, K, Pa, kg/m^3, Pa*s, kg/s, m^3/s, etc.

In order to determine errors of instruments and corrections to values of measured variables, all measuring instruments are regularly subjected to verification according to standard or reference instruments.

Accuracy is an agreement of a measurement with the true value of a measured quantity. We should know how accurate the measuring device can measure a process parameter. In general form accuracy is usually expressed as a percentage of the instrument span (the range of instrument measurement capability) or full-scale

$$\delta = \frac{\left|A_m - A_a\right|}{A_{\max} - A_{\min}} * 100\%, \tag{1.3}$$

where:

$A_{\max}$ and $A_{\min}$ - maximum and minimum values of a process variable, respectively, which can be measured by a measuring instrument;

$A_{\max} - A_{\min}$ - a span or full-scale of a measuring instrument.

There is another characteristic of a measurement process.

Repeatability, according to a British Standard definition, "is the ability of a measuring instrument to give identical indications, or responses, for repeated applications of the same value of the measured quantity under stated conditions of use. If an accuracy is the ability of the device or an instrument to tell the truth about the process parameters, the repeatability is the ability of an instrument to stick the same story. Instruments as well as people are sometimes capable to tell the same lie over and over again. Good repeatability is no guarantee of good accuracy, although poor repeatability is a sure sign of poor accuracy. In other words, good repeatability is a necessary, but not sufficient condition of good accuracy." (Hayward A.T.J., *Repeatability and Accuracy*, 1977).

Sensitivity is a measure of the change in output of an instrument for a change in input. In other words, it is the ability of a measuring device to detect small differences in a quantity being measured. High sensitivity is desirable in an instrument because a large change in output for a small change in input implies that a measurement may be taken easily.

Example: if a very small change in pressure applied to two pressure gages results a perceptible change in the indications of one instrument and not in the other, it is said that the former is more sensitive instrument. The most sensitive instrument equipment may not always lead to the most precise or the most accurate results. The *sensitivity* of a measuring device with a *linear static characteristic* is equal to the *ratio between the variation of the output signal of the measuring instrument and the variation of its input signal which causes that variation of the output signal*

$$S = \frac{dY}{dX} = \frac{\Delta Y}{\Delta X}, \tag{1.4}$$

where: S - the sensitivity of an instrument;
ΔX - the variation of an input signal;
ΔY - the variation of an output signal.

If in the temperature range from 0 to 50 °C temperature variation in one degree Celsius causes the change in an output signal of a temperature transducer in 4 mV, it is said that the sensitivity of this transducer is equal to 4 mV/°C *in the above temperature range*. Why we say *"in the above temperature range"*? It is known that static behaviour of a system or a measuring instrument can be expressed graphically (see **Fig. 1.5**). It is not correct to say that thermocouple, which correlation of *thermoelectromotive force* vs *temperature* is graphically shown in this figure, has the same sensitivity in the entire temperature range. Sensitivity of a mesuring instrument (or sensor, or transducer) has different values when its static characteristic is non-linear, and it is constant in the case of a linear static characteristic.

2. Representation of instruments in flowcharts.

2.1. Symbols for instrumentation layouts.

For Chemical Engineers involved in either design or production activity, it is necessary to be able to distinguish various types of field and indoor instrumentation and control systems used for particular industrial applications. In order to make layouts uniform and to visualise the process control system a set of symbols was introduced. The following symbols were taken from: Australian Standard - AS 1101.6-1989, ***Graphical Symbols for general engineering. Part 6: Process*** *measurement control functions and instrumentation*, Standards Australia, 1989, 52 pp.

Figure 2.1. presents symbols for industrial instrumentation.

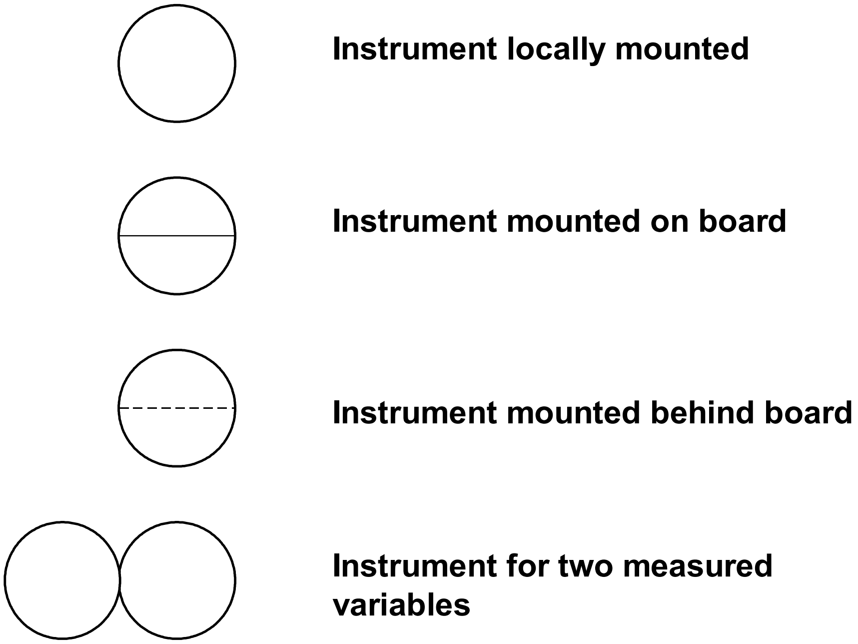


Figure 2.1. Symbols for instrumentation.

Diameter of a circle for the symbol is equal to **10 mm**. Meanings of identification letters for these symbols are presented in **Table 2.1.**

To better understand how these symbols are placed in process control and instrumentation flowcharts I decided to give several examples for measuring and control of process variables in a variety of industrial processes.

Table 2.1. Meanings of identification letters.

First Letter			**Succeeding Letters**		
Measured or initiating variable		Modifier	Readout or passive function	Output function	Modifier
A	Analysis		Alarm		
B	Burner flame		User's choice	User's choice	User's choice
C	Conductivity (electrical)			Control	
D	Density (mass), specific gravity	Differential			
E	Voltage (e.m.f.)		Primary element		
F	Flow rate	Ratio (fraction)			
G	Gaging (dimensional)		Glass		
H	Hand (manually initiated)				High
I	Current (electrical)		Indicate		
J	Power	Scan			
K	Time or time schedule			Control station	
L	Level		Light		low
M	Moisture or humidity				Middle or intermediate
N	User's choice		User's choice	User's choice	User's choice
O	User's choice		Orifice (restriction		
P	Pressure or vacuum		Point (test connection)		
Q	Quantity or event	Integrate or totalise			
R	Radioactivity		Record or print		
S	Speed or frequency	Safety		Switch	
T	Temperature			Transmit	
U	Multivariable		Multifunction	Multifunction	Multifunction
V	Viscosity			Valve, damper	

Table 2.1. (Continued). Meanings of identification letters.

First Letter			Succeeding Letters		
Measured or initiating variable		Modifier	Readout or passive function	Output function	Modifier
W	Weight or force				
X	Unclassified		Unclassified	Unclassified	Unclassified
Y	User's choice			Relay or compute	
Z	Position			Drive, actuate	

2.2. Control loop configurations for chemical process variables.

2.2.1. Level control.

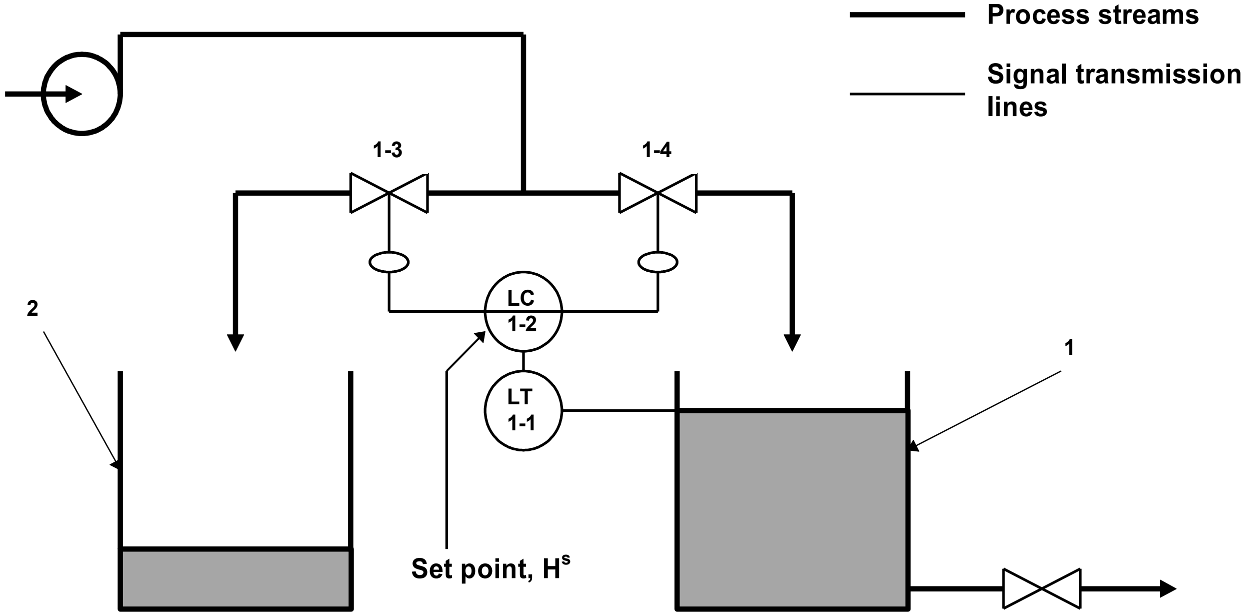


Figure 2.2. On-off level control loop.

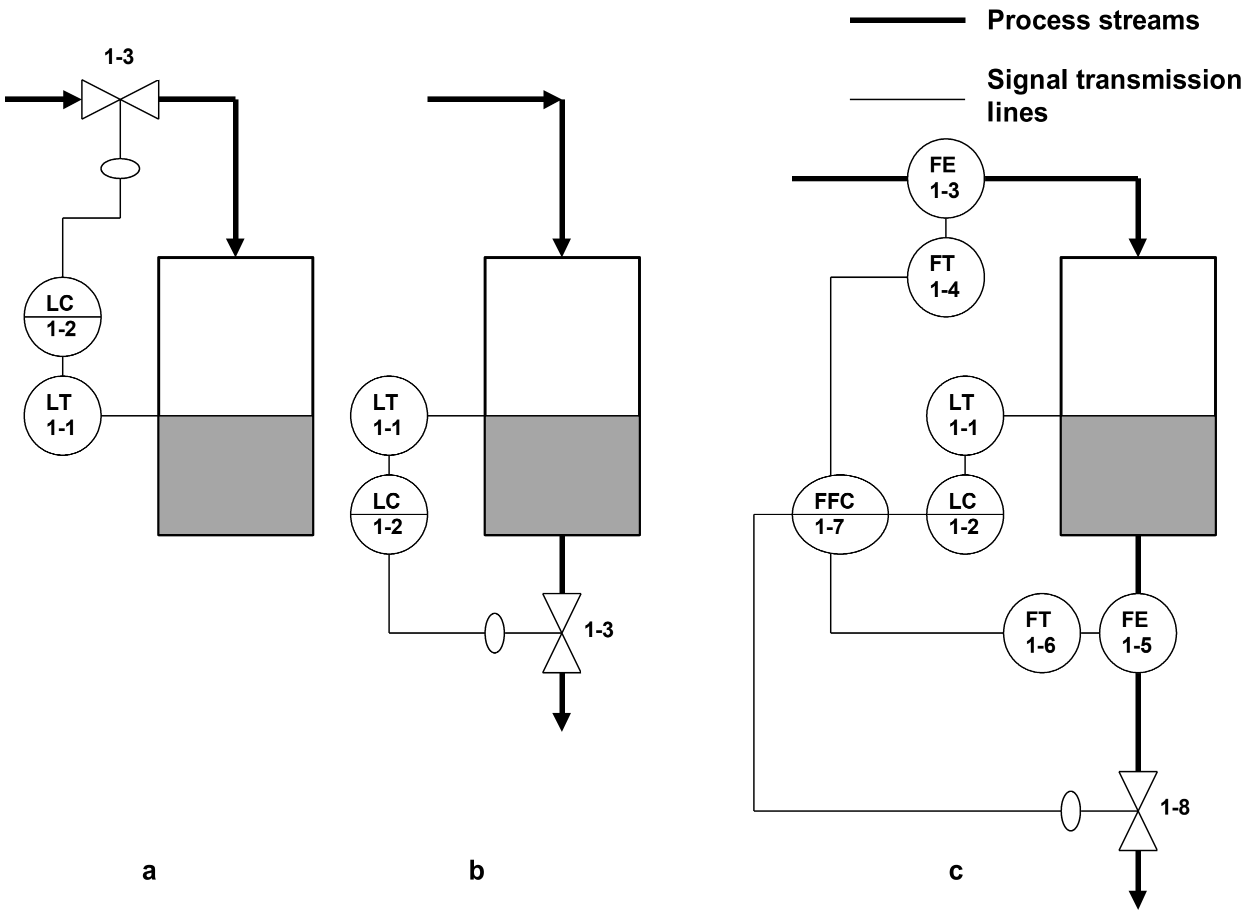


Figure 2.3. Control loops for continuous level control.
a - by the control of an inlet stream; **b** - by the control of an outlet stream;
c - cascade control loop.

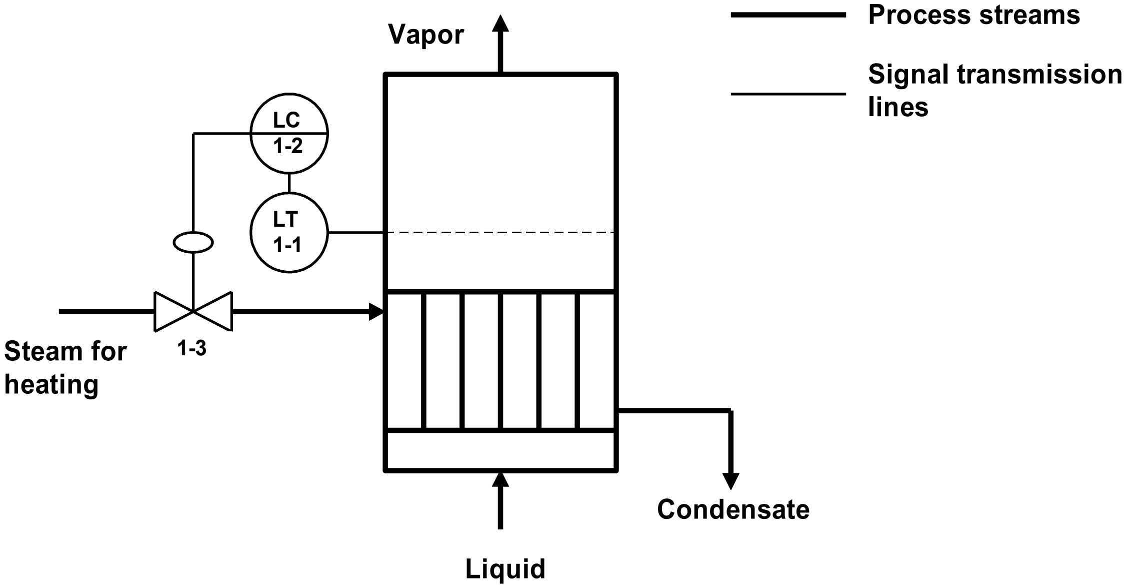


Figure 2.4. Level control in evaporator.

2.2.2. Pressure control

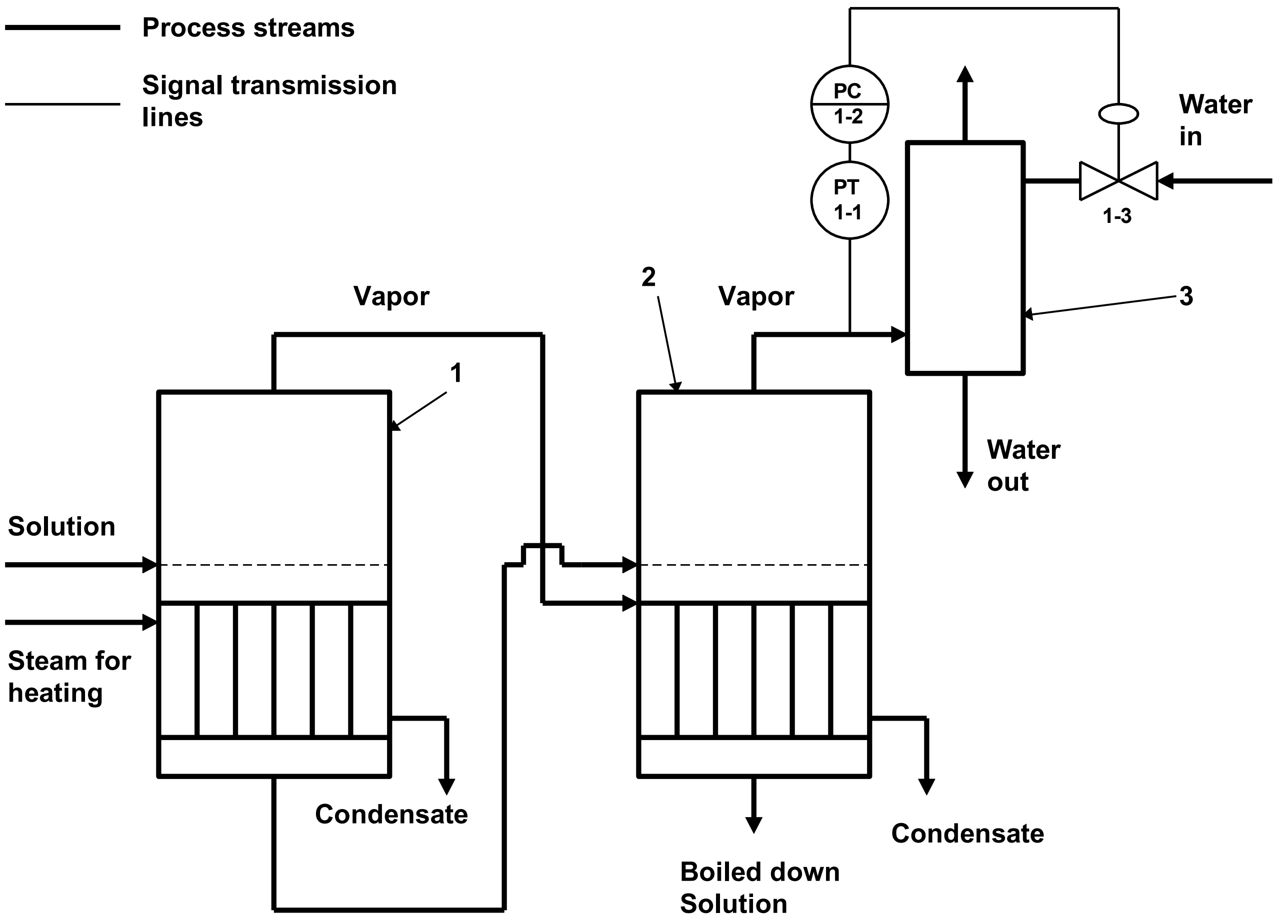


Figure 2.5. Pressure control loop for evaporating unit.
1, **2** - evaporating units; **3** - barometric condenser.

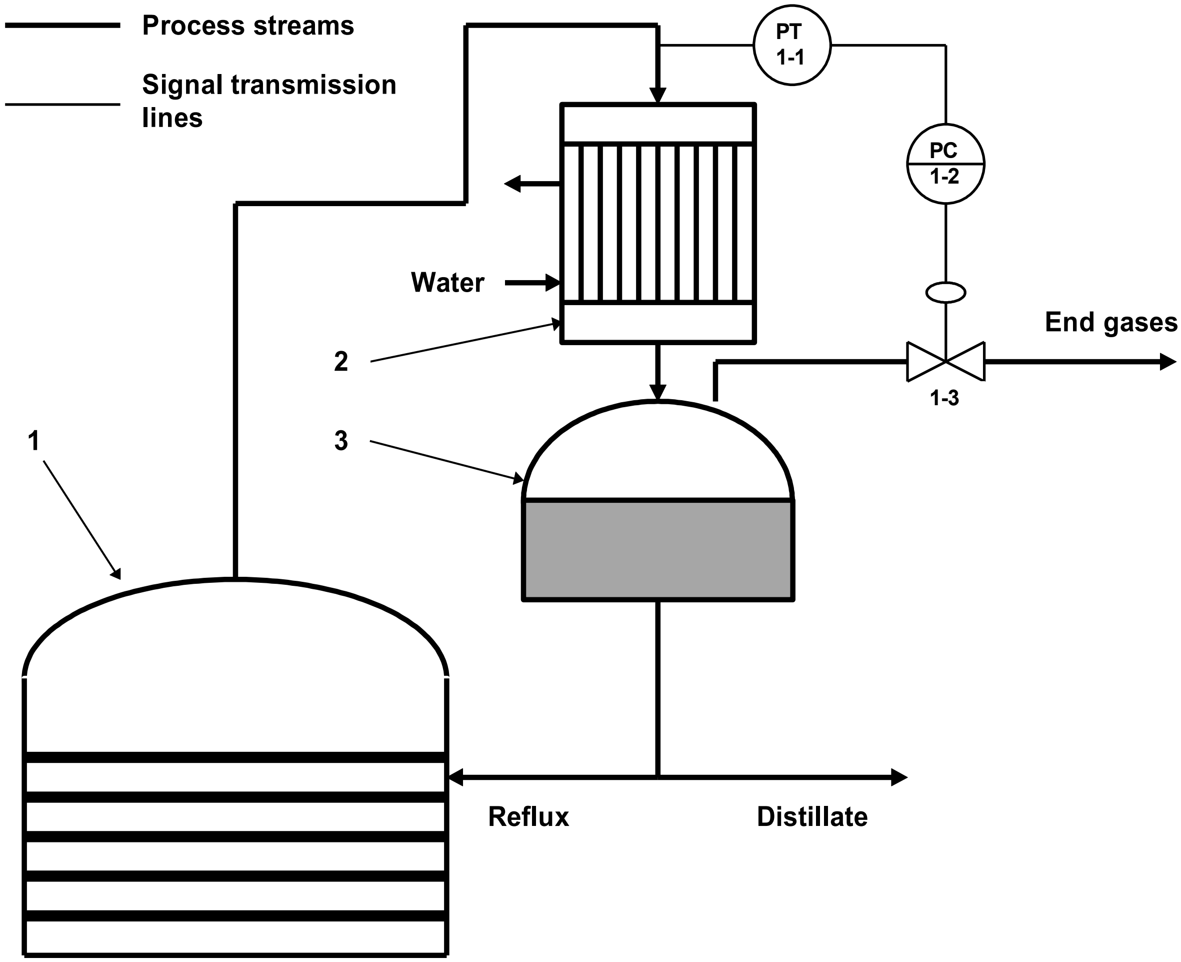


Figure 2.6. Pressure control in the distillation column.
1 - distillation column; **2** - reflux column; **3** - reflux tank;

2.2.3. Temperature control

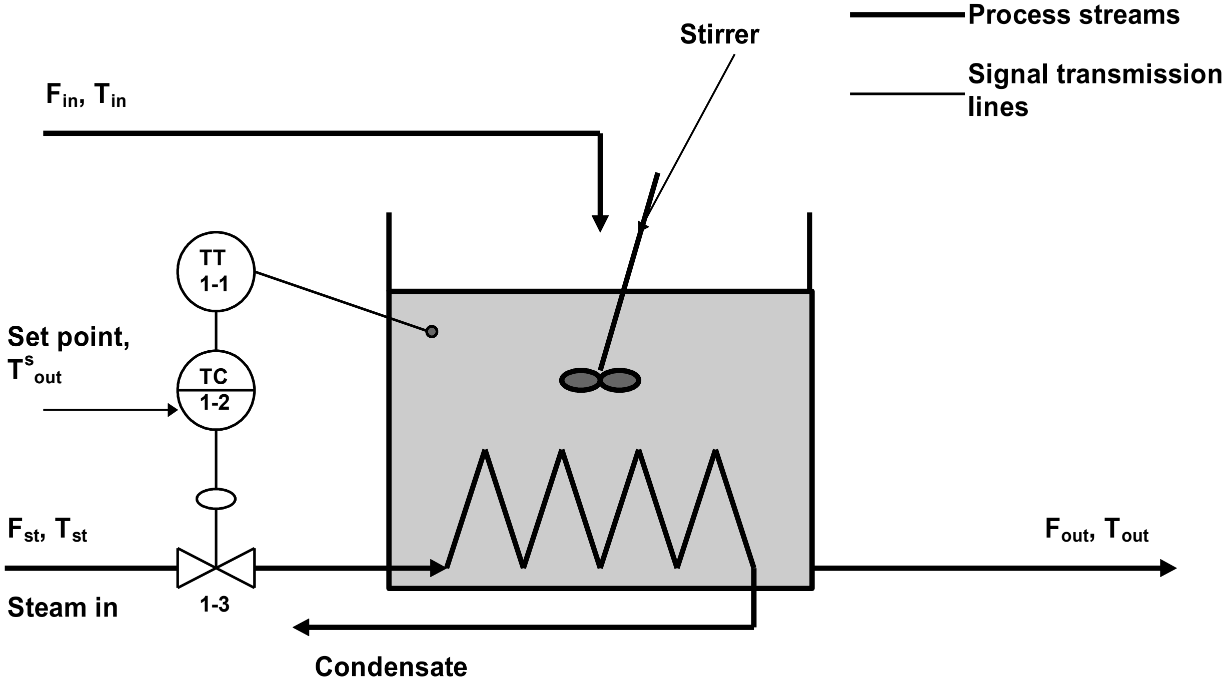


Figure 2.7. Single loop control system for a stirred tank.

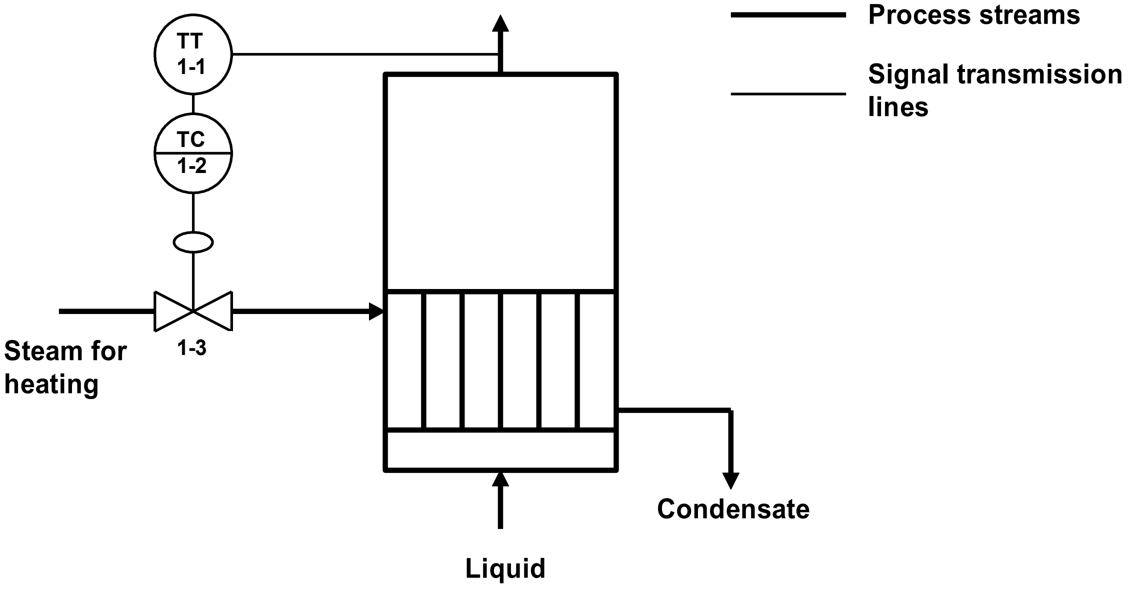


Figure 2.8. Single loop control system for heat exchanger.

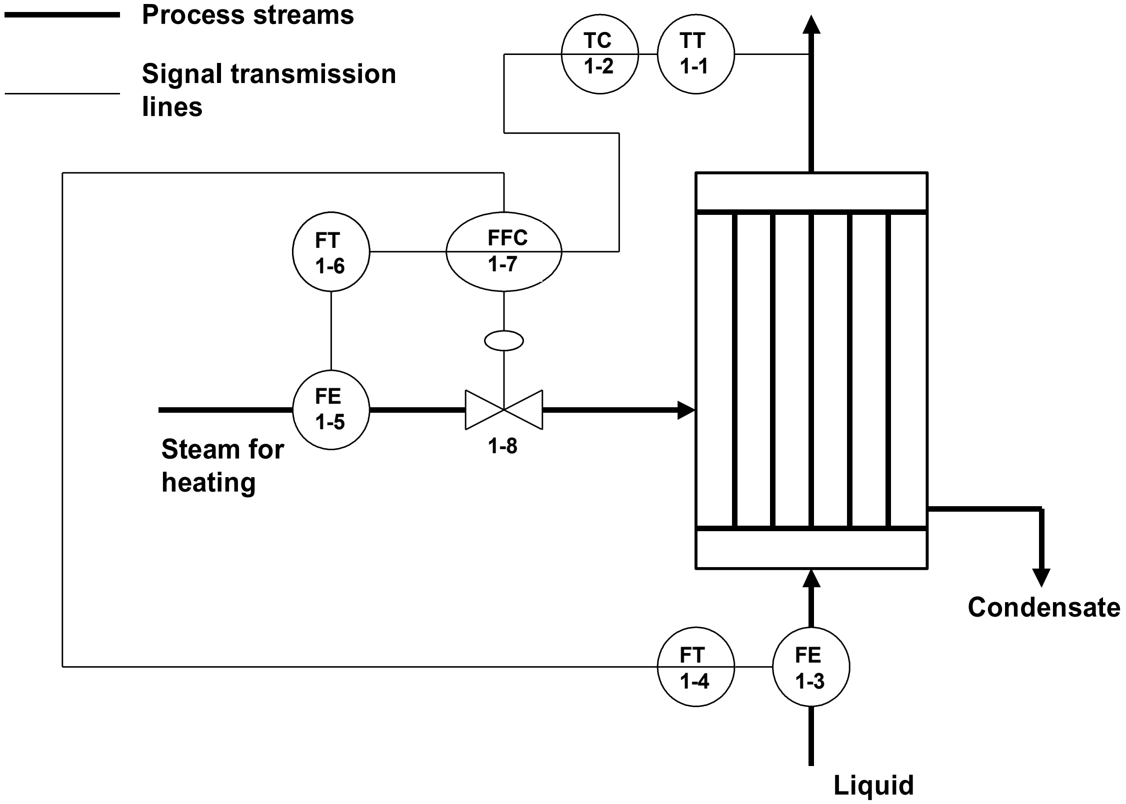


Figure 2.9. Cascade control system for heat exchanger.

2.2.4. Flow control

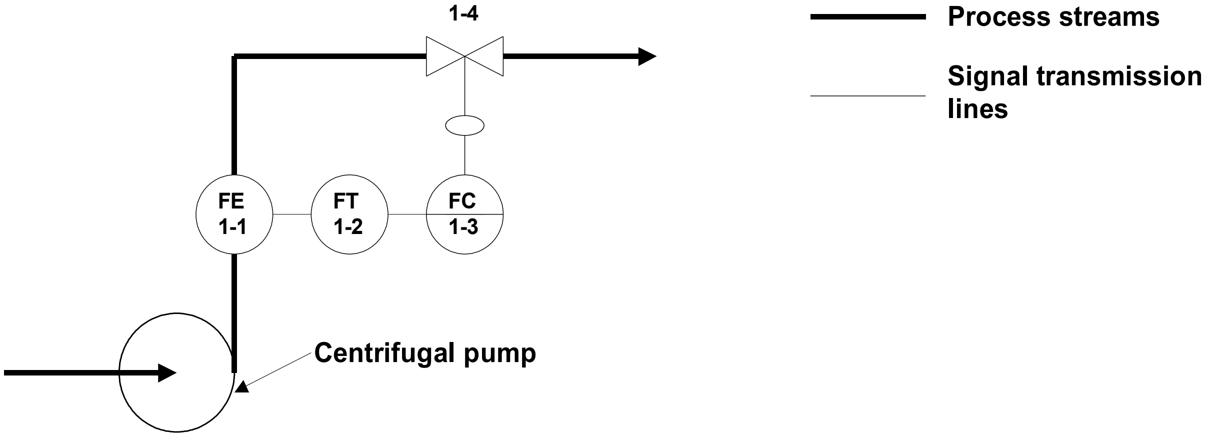


Figure 2.10. Flow control by throttling the stream after the centrifugal pump.

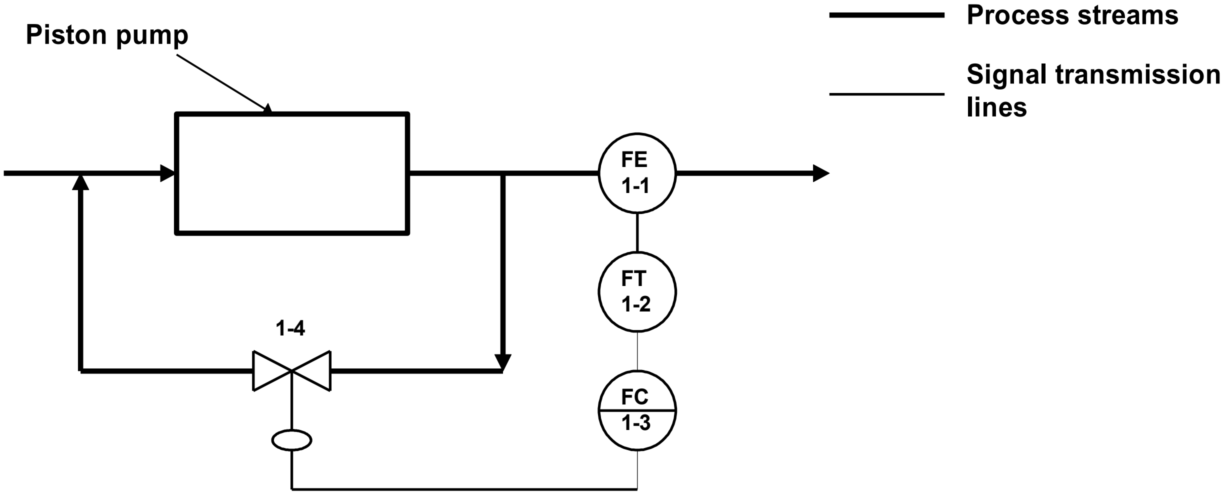


Figure 2.11. Flow control using by-pass pipe-line in the case of the piston pump.

2.2.5. pH control

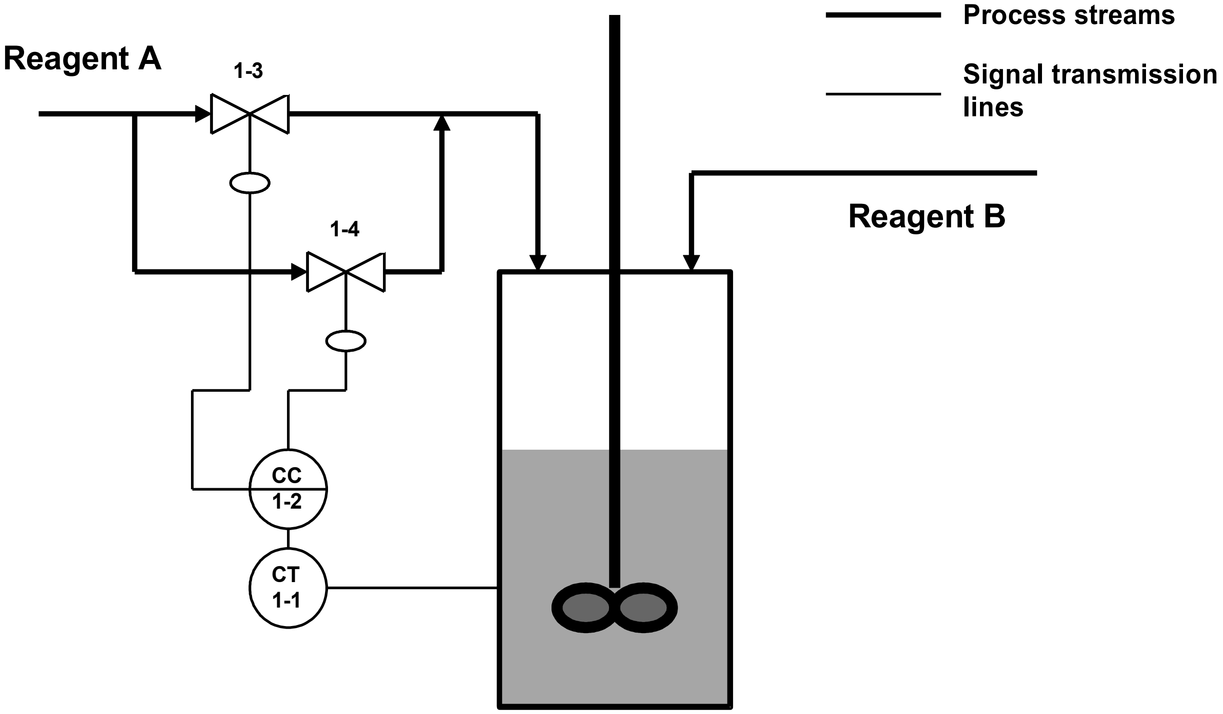


Figure 2.12. pH control system.

2.2.6. Composition control

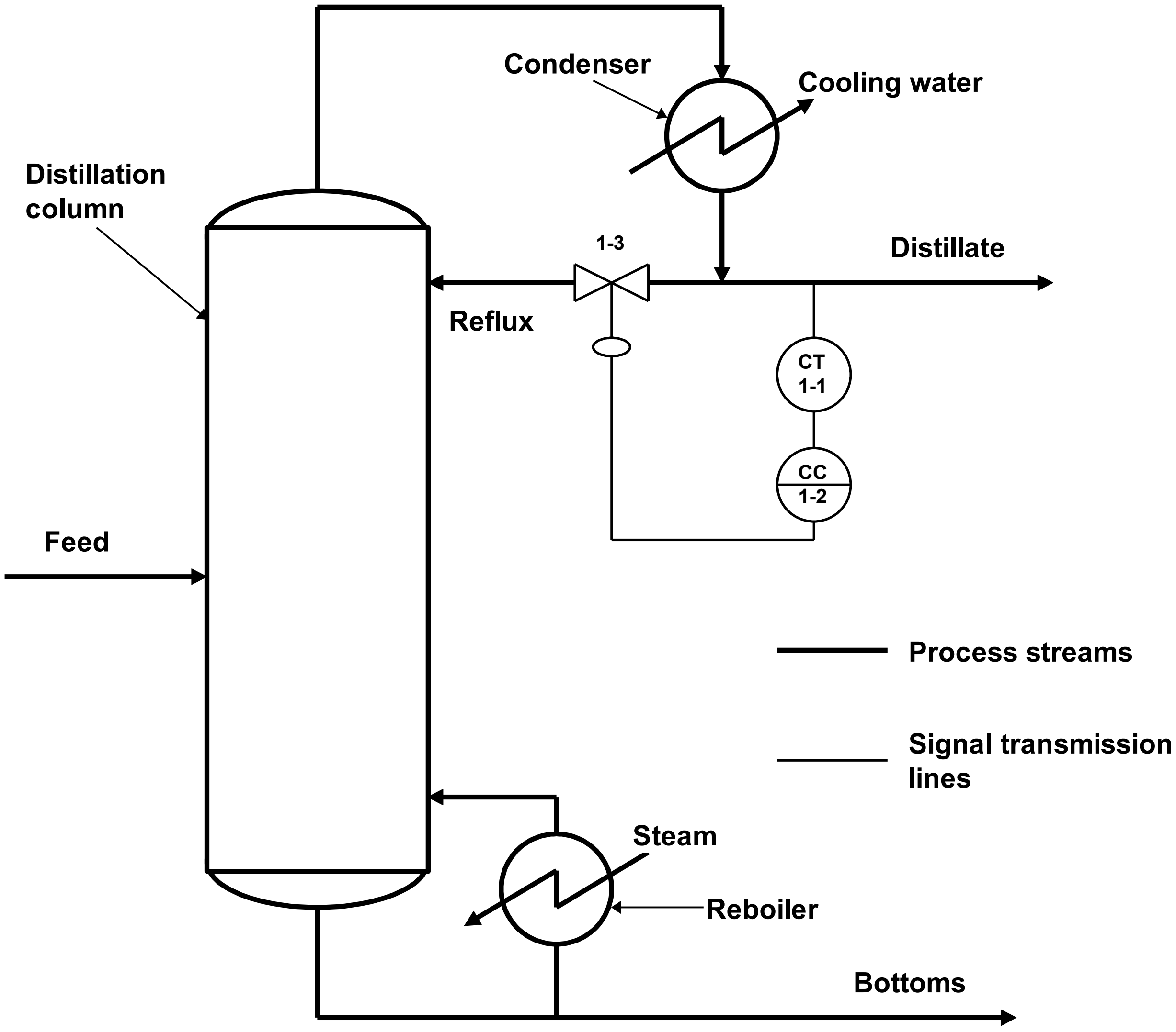


Figure 2.13. Feedback system for composition control.

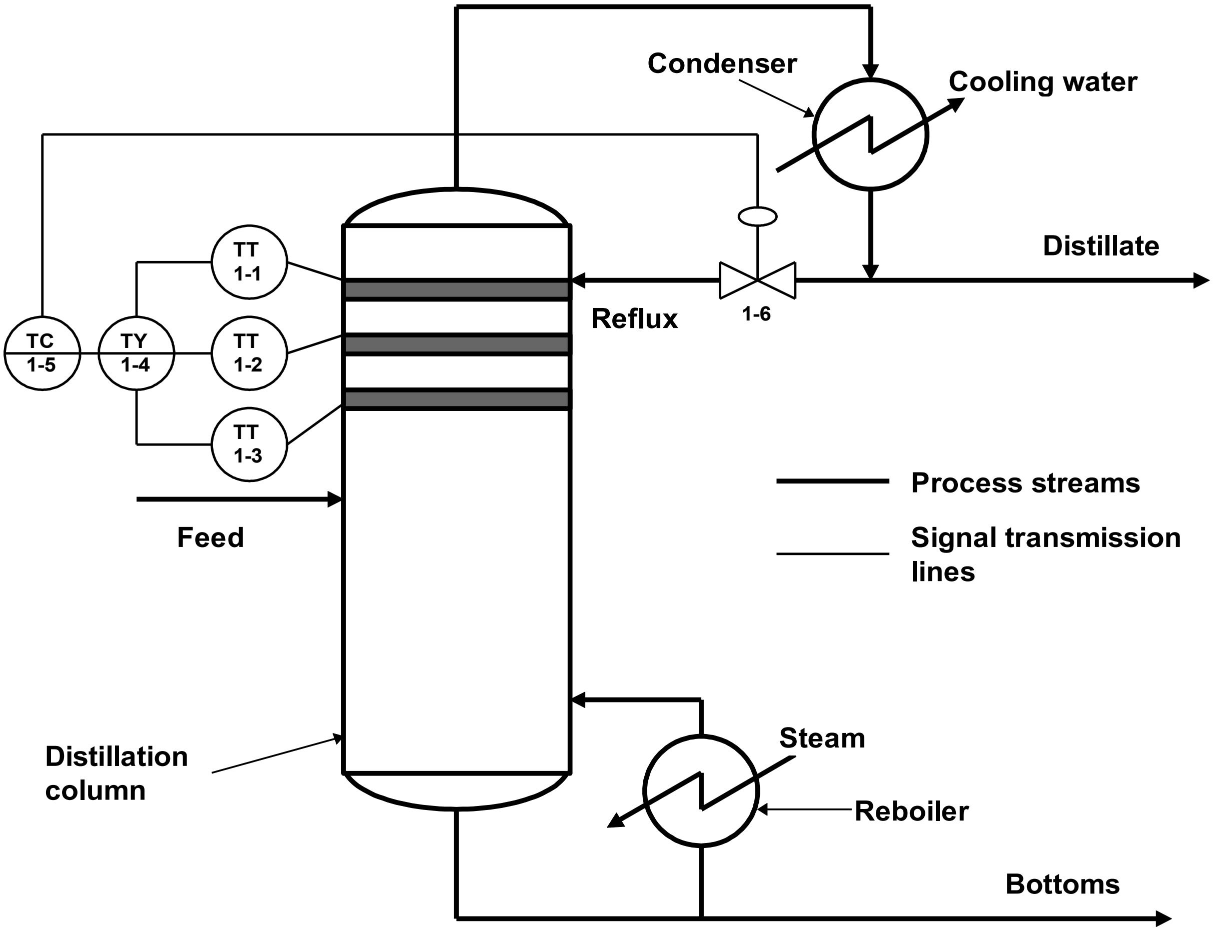


Figure 2.14. Inferential system for composition control.

2.3. Various control loops for continuous a stirred tank reactor

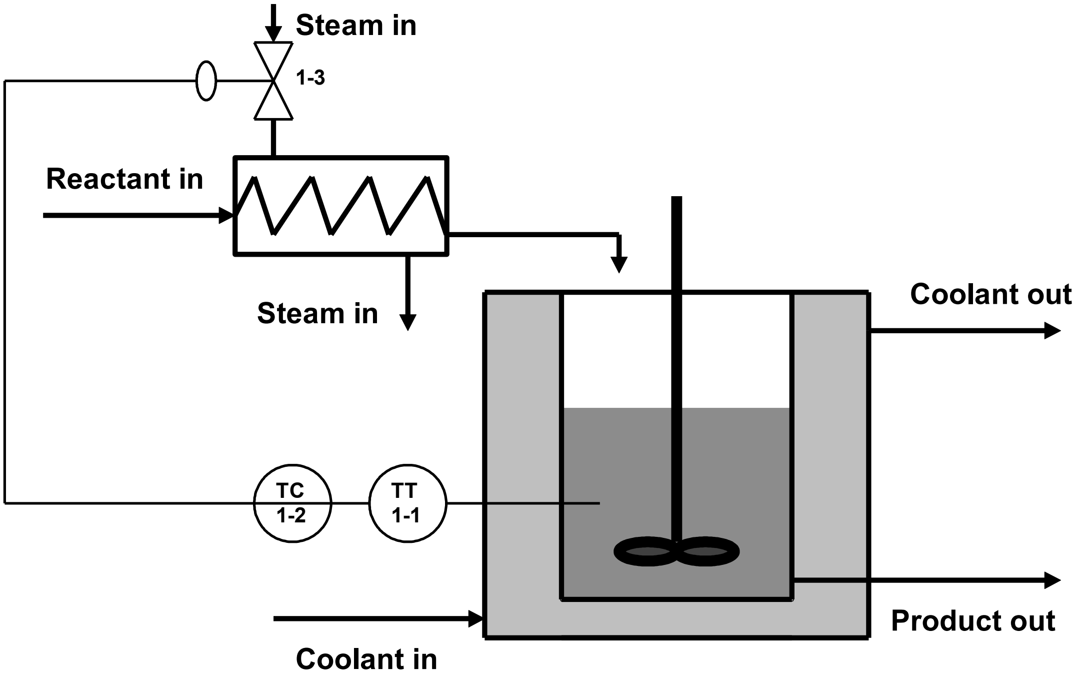


Figure 2.15. Control loop configuration for the CSTR.

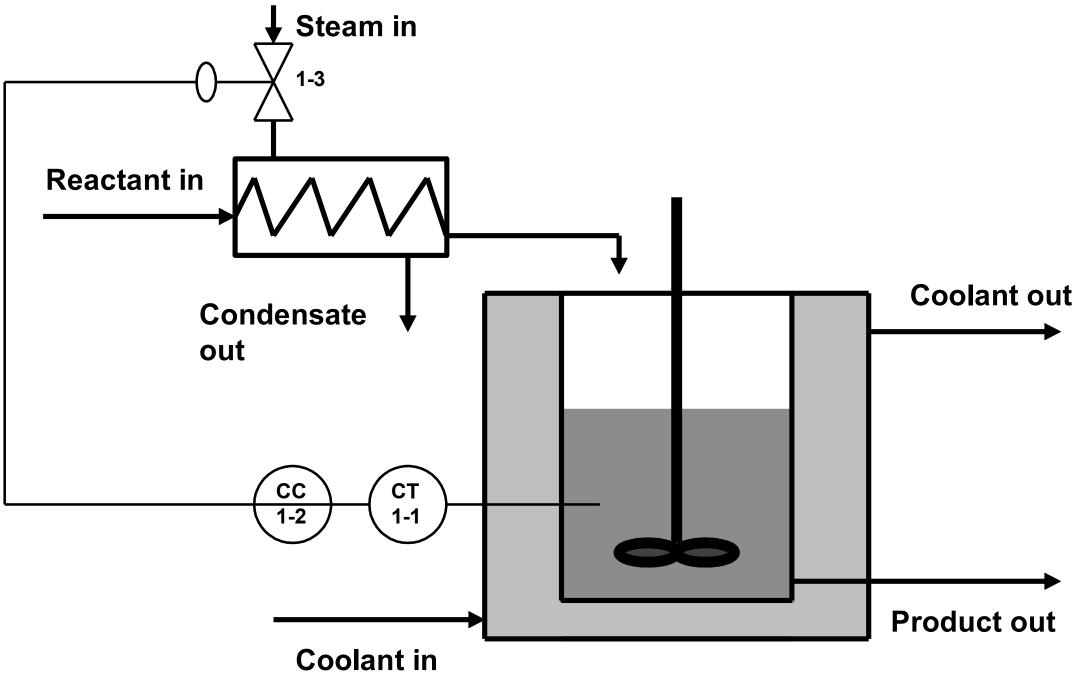


Figure 2.16. Control loop configuration for the CSTR.

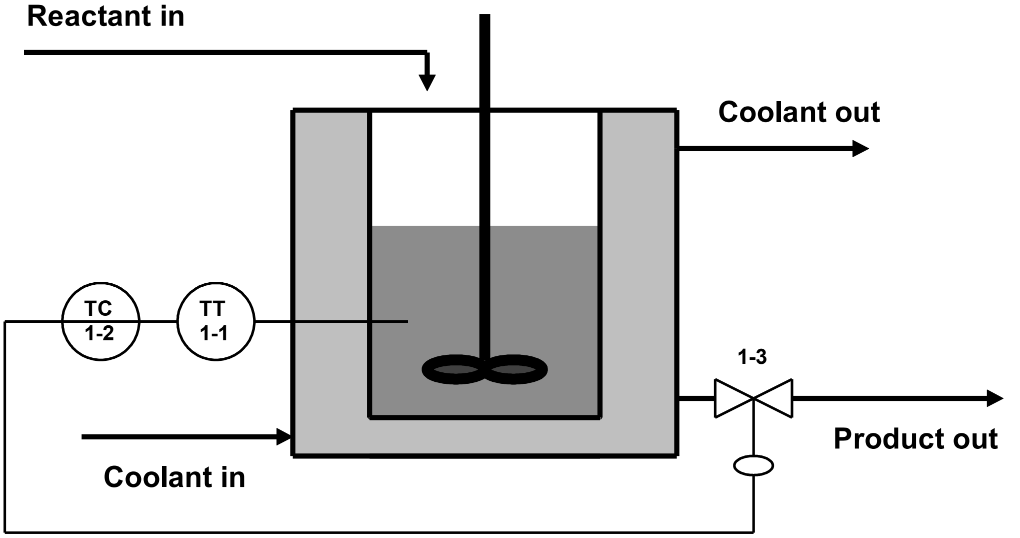


Figure 2.17. Control loop configuration for the CSTR.

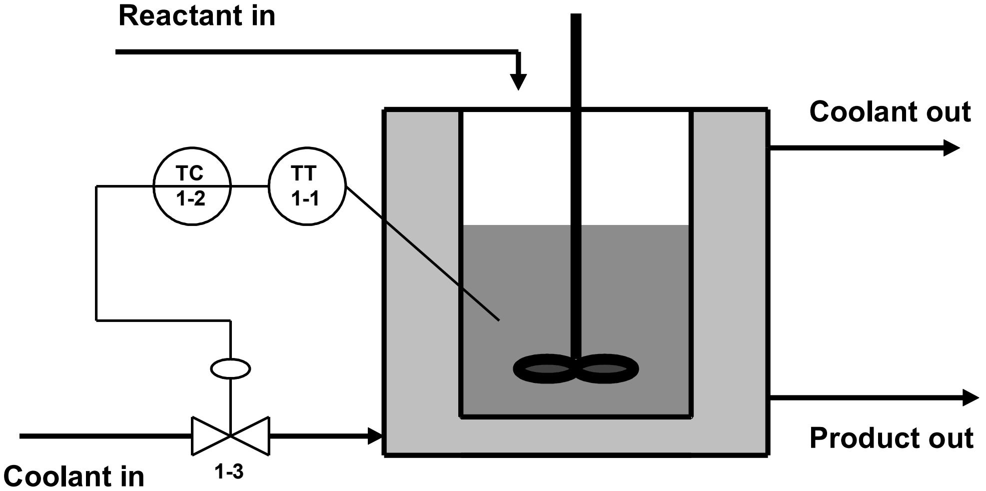


Figure 2.18. Control loop configuration for the CSTR.

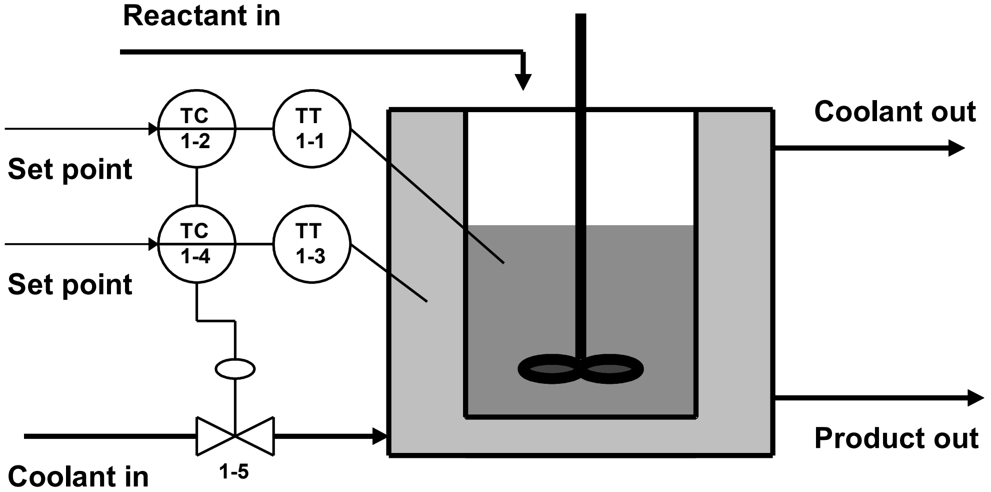


Fig. 2.19. Control loop configuration for the CSTR.

2.4. Control of furnaces.

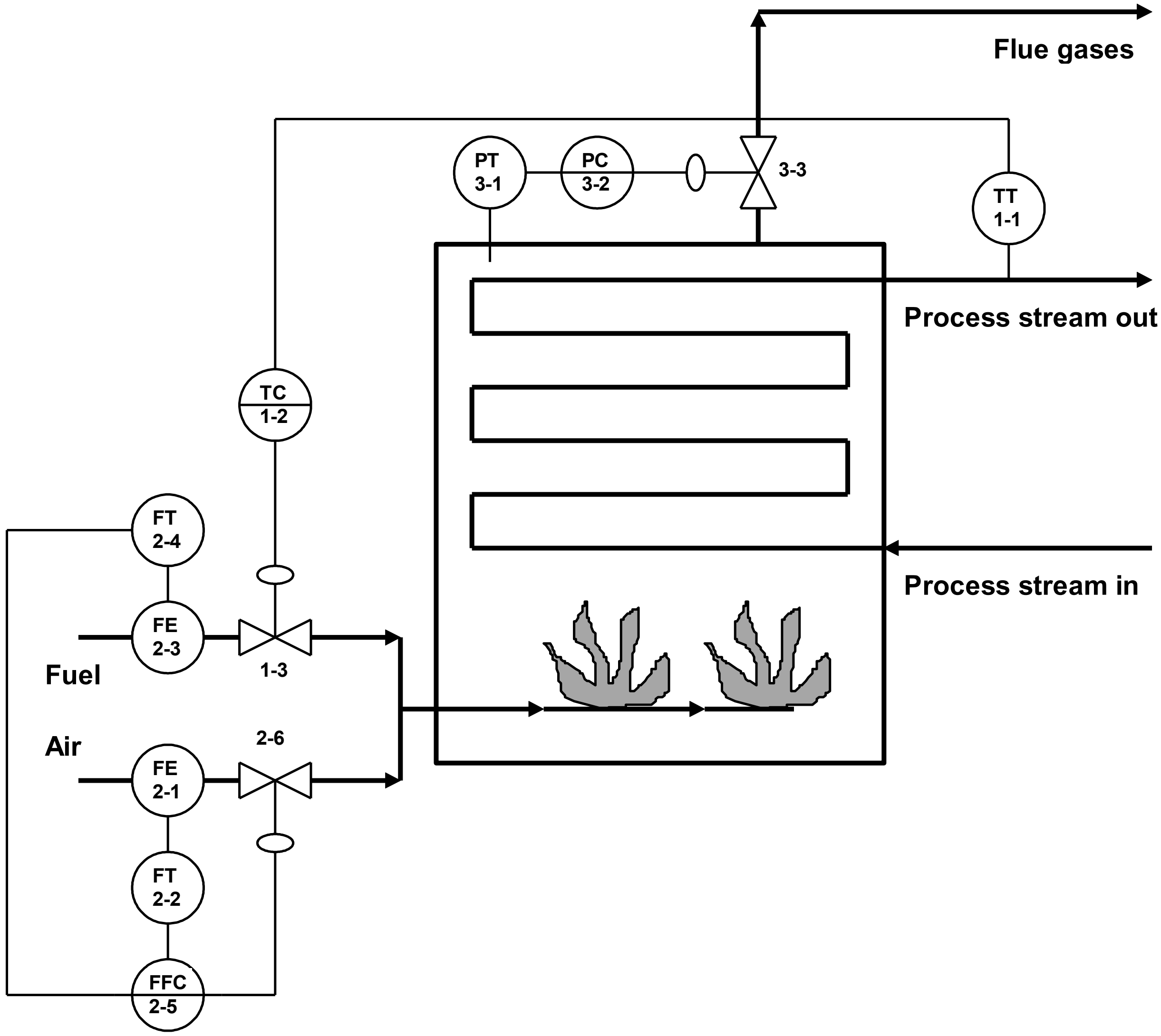
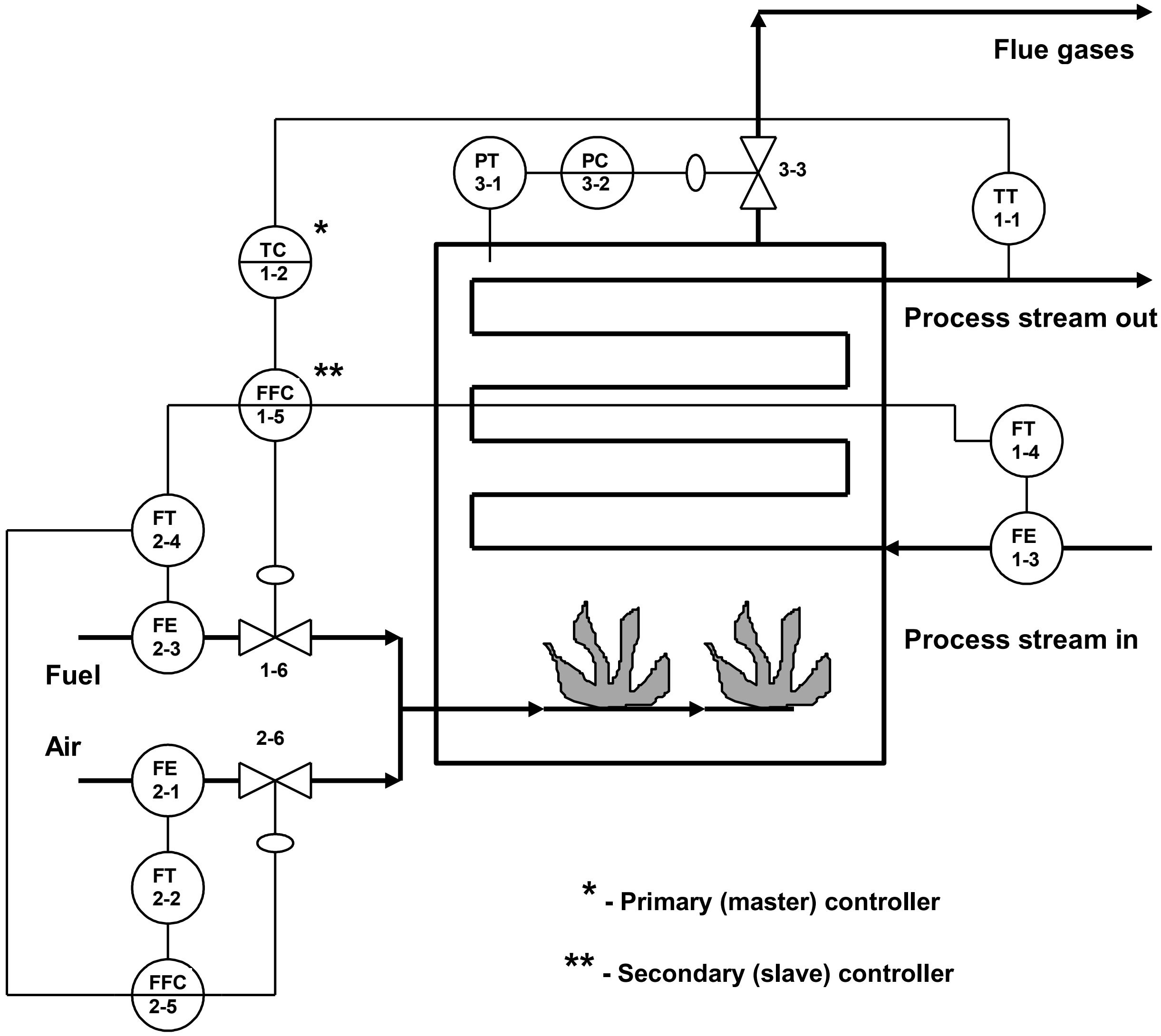


Figure 2.20. Control system with three single loops.



* - Primary (master) controller

** - Secondary (slave) controller

Figure 2.21. Cascade control system to regulate the temperature of a process stream leaving the furnace.

2.5. Control of distillation columns.

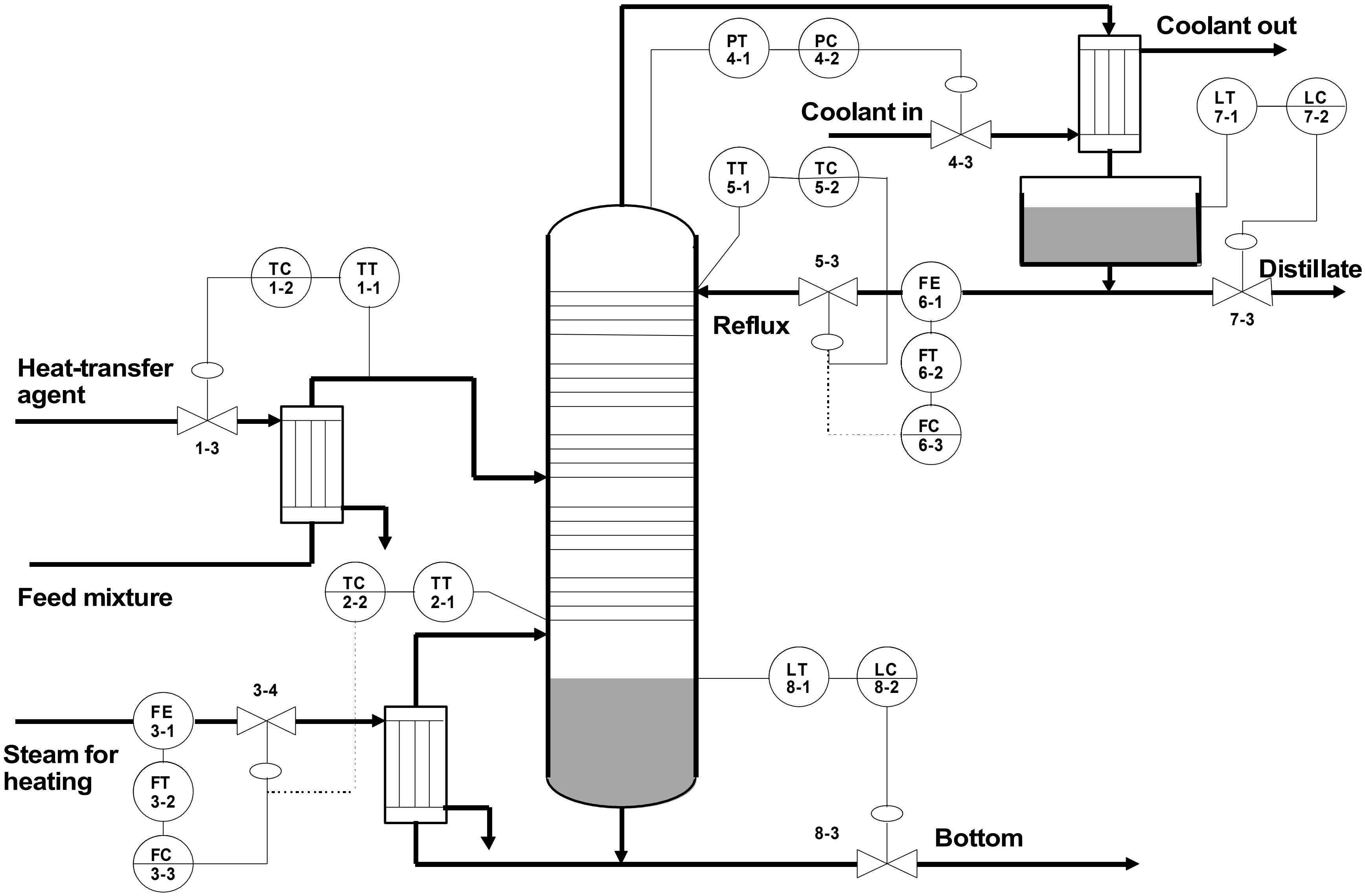

Coolant out
PT 4-1
PC 4-2
Coolant in
4-3
LT 7-1
LC 7-2
TT 5-1
TC 5-2
5-3
FE 6-1
Distillate
7-3
Reflux
FT 6-2
FC 6-3
TC 1-2
TT 1-1
Heat-transfer agent
1-3
Feed mixture
TC 2-2
TT 2-1
3-4
FE 3-1
Steam for heating
FT 3-2
FC 3-3
LT 8-1
LC 8-2
8-3
Bottom

Figure 2.22. Distillation column with six single-loop control systems.

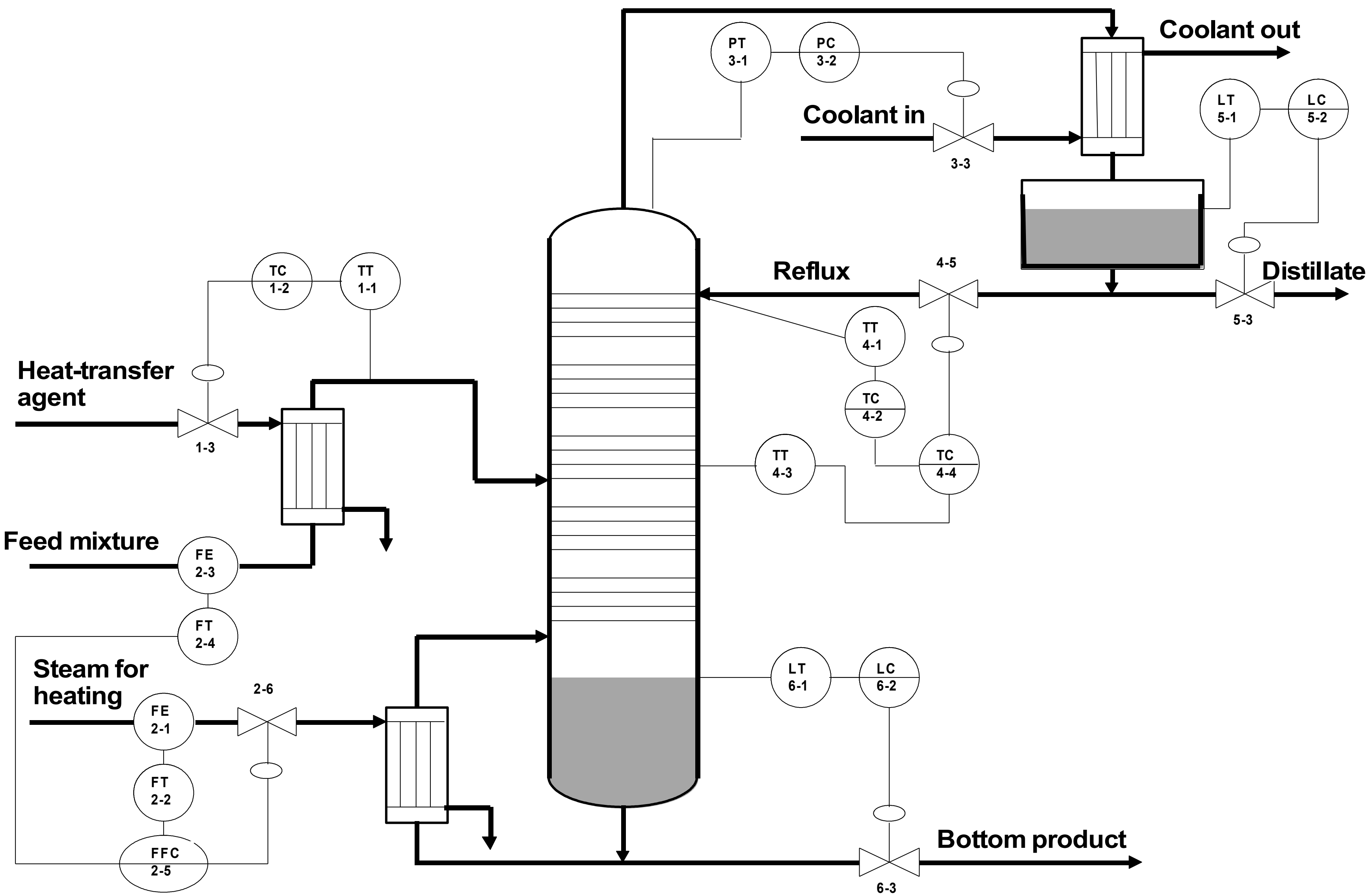

Coolant out
PT 3-1
PC 3-2
Coolant in
3-3
LT 5-1
LC 5-2
Reflux
4-5
Distillate
5-3
TC 1-2
TT 1-1
TT 4-1
TC 4-2
Heat-transfer agent
1-3
TT 4-3
TC 4-4
Feed mixture
FE 2-3
FT 2-4
Steam for heating
2-6
FE 2-1
FT 2-2
FFC 2-5
LT 6-1
LC 6-2
Bottom product
6-3

Figure 2.23. Distillation column with single-loop and cascade control systems.