Lesson 1: Processes and Systems

1.0 context and direction

Process control is an application area of chemical engineering - an identifiable specialty for the ChE. It combines chemical process knowledge (how physics, chemistry, and biology work in operating equipment) and an understanding of dynamic systems, a topic important to many fields of engineering. Thus study of process control allows chemical engineers to span their own field, as well as form a useful acquaintance with allied fields. Practitioners of process control find their skills useful in design, operation, and troubleshooting - major categories of chemical engineering practice.

Process control, like any coherent topic, is an integrated body of knowledge - it hangs together on a multidimensional framework, and practitioners draw from many parts of the framework in doing their work. Yet in learning, we must receive information in sequence - following a path through multidimensional space. It is like entering a large building with unlighted rooms, holding a dim flashlight and clutching a vague map that omits some of the stairways and passages. How best to learn one's way around?

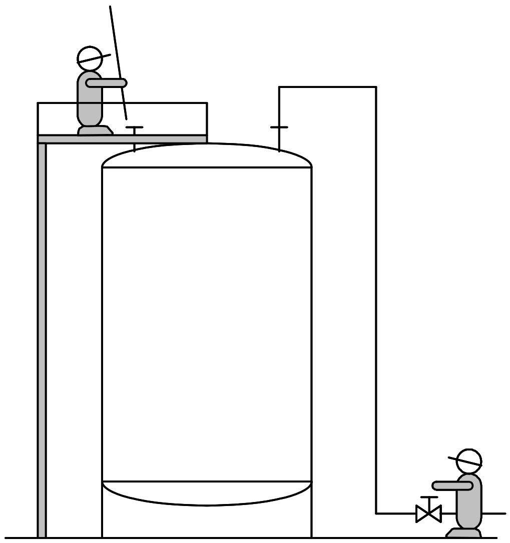
In these lessons we will attempt to move through a significant portion of the structure - say, half a textbook - in about two weeks. Then we will repeat the journey several times, each time inspecting the rooms more thoroughly. By this means we hope to gain, from the start, a sense of doing an entire process control job, as well as approach each new topic in the context of a familiar path.

1.1 the job we will do, over and over

We encounter a process, learn how it behaves, specify how we wish to control it, choose appropriate equipment, and then explore the behavior under control to see if we have improved things.

1.2 introducing a simple process

A large tank must be filled with liquid from a supply line. One operator stands at ground level to operate the feed valve. Another stands on the tank, gauging its level with a dipstick. When the tank is near full, the stick operator will instruct the other to start closing the valve. Overfilling can cause spills, but underfilling will cause later process problems.



To learn how the process works, we write an overall material balance on the tank.

$$\frac{d}{dt}\rho V = \rho F_i \tag{1.2-1}$$

The tank volume V can be expressed in terms of the liquid level h. The inlet volumetric flow rate F_i may vary with time due to supply pressure fluctuations and valve manipulations by the operator. The liquid density depends on the temperature, but will usually not vary significantly with time during the course of filling. Thus (1.2-1) becomes

$$A\frac{dh}{dt} = F_i(t) \tag{1.2-2}$$

We integrate (1.2-2) to find the liquid level as a function of time.

$$h = h(0) + \frac{1}{A}\int_0^t F_i(t)dt \tag{1.2-3}$$

1.3 planning a control scheme

Clearly the liquid level h is important, and we will call it the controlled variable. Our control objective is to bring h quickly to its target value h_r and not exceed it. (To be realistic, we would specify allowable limits $\pm\,\delta h$ on h_r.) We will call the volumetric flow F_i the manipulated variable, because we adjust it to achieve our objective for the controlled variable.

The existing control scheme is to measure the controlled variable via dipstick, decide when the controlled variable is near target, and instruct the valve operator to change the manipulated variable. The scheme suffers from

- delay in measurement. Overfilling can occur if the stick operator cannot complete the measurement in time.
- performance variations. Both stick and valve operators may vary in attentiveness and speed of execution.
- resources required. There are better uses for operating personnel.
- unsafe conditions. There is too much potential for chemical exposure.

A new scheme is proposed: put a timer on the valve. Calculate the time required for filling from (1.2-3). Close the valve when time has expired.

The timing scheme would no longer require an operator to be on the tank top, and with a motor-driven valve actuator the entire operation could be directed from a control room. These are indeed improvements. However, the timing scheme abandons a crucial virtue of the existing scheme: by measuring the controlled variable, the operators can react to unexpected disturbances, such as changes in the filling rate. Using knowledge of the controlled variable to motivate changes to the manipulated variable is a fundamental control structure, known as feedback control. The proposed timing scheme has no feedback mechanism, and thus cannot accommodate changes to $h(0)$ and $F_i(t)$ in (1.2-3).

An alternative is to build on the feedback already inherent in the two-operator scheme, but to improve its operation. We propose an automatic controller that behaves according to the following controller algorithm:

$$\begin{array}{ll} h < h_{near} & F_i = F_{max} \\ h > h_{near} & F_i = F_{max}\dfrac{h_r - h}{h_r - h_{near}} \end{array} \tag{1.3-1}$$

Algorithm (1.3-1) is an idealization of what the operators are already doing: filling occurs at maximum flow until the level reaches a value h_{near}. Beyond this point, the flow decreases linearly, reaching zero when h reaches the target h_r. The setting of h_{near} may be adjusted to tune the control performance.

1.4 choosing equipment

We need a sensor to replace the dipstick, a valve actuator to replace the valve operator, and a controller mechanism to replace the stick operator. We imagine a buoyant object floating on the liquid surface. The float is linked to a lever that drives the valve stem. When the liquid level is low, the float rests above it on a structure so that the valve is fully open.

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(To see a cut-away diagram of a toilet, go to
http://www.toiletology.com/lg-views.shtml#cutaway2x)

1.5 process behavior under automatic control

Typically these things work quite well. We predict its performance by combining our process model (1.2-2) with the controller algorithm (1.3-1), which eliminates the manipulated variable between the equations. We take the simple case in which F_{max} does not vary during filling due to pressure fluctuations, etc. For h less than h_{near},

$$A\frac{dh}{dt} = F_{max} \qquad h(0) = \text{known}$$
$$h = h(0) + \frac{F_{max}}{A}t \tag{1.5-1}$$

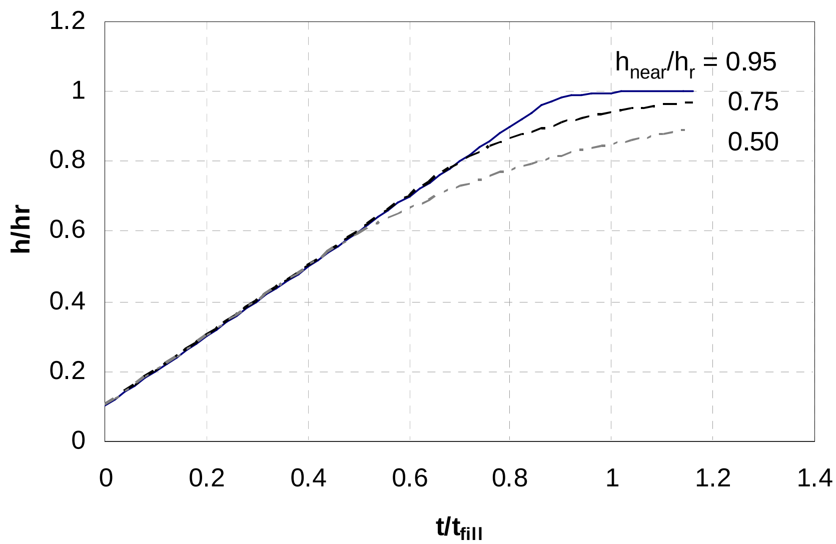
Equation (1.5-1) can be used to calculate t_{near}, the time at which h reaches h_{near}. For h greater than h_{near},

$$A\frac{dh}{dt} = F_{max}\frac{h_r - h}{h_r - h_{near}} \qquad h(t_{near}) = h_{near}$$
$$h = h_r - \left(h_r - h_{near}\right)\exp\left[\frac{-h_r(t - t_{near})}{t_{fill}\left(h_r - h_{near}\right)}\right] \tag{1.5-2}$$

where the parameter t_{fill} is the time required for the level to reach h_r at flow F_{max}, starting from an empty tank.

$$t_{fill} = \frac{Ah_r}{F_{max}} \tag{1.5-3}$$

The plot shows the filling profile from $h(0) = 0.10h_r$ with several values of h_{near}/h_r. Certainly the filling goes faster if the flow can go instantaneously from F_{max} to zero at h_r; however this will not be practical, so that h_{near} will be less than h_r.

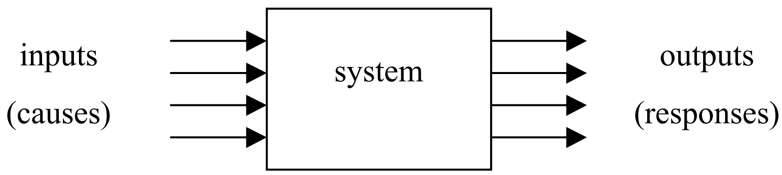


1.6 defining 'system'

In Section 1.2, we introduced a process - a tank with feed piping - whose inventory varied in time. We thought of the process as a collection of equipment and other material, marked off by a boundary in space, communicating with its environment by energy and material streams.

'Process' is a good notion, important to chemical engineers. Another useful notion is that of 'system'. <u>A system is some collection of equipment and operations, usually with a boundary, communicating with its environment by a set of input and output signals.</u> By these definitions, a process is a type of system, but *system* is more abstract and general. For example, the system boundary is often tenuous: suppose that our system comprises the equipment in the plant and the controller in the central control room, with radio communication between the two. A physical boundary would be in two pieces, at least; perhaps we should regard this system boundary as partly physical (around the chemical process) and partly conceptual (around the controller).

Furthermore, the inputs and outputs of a system need not be material and energy streams, as they are for a process. System inputs are "things that cause" or "stimuli"; outputs are "things that are affected" or "responses".



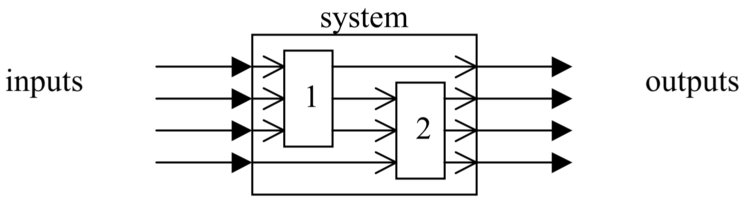
To approach the problem of controlling our filling process in Section 1.3, we thought of it in system terms: the primary output was the liquid level h -- not a stream, certainly, but an important response variable of the system -- and inlet stream F_i was an input. And peculiar as it first seems, if the tank had an outlet flow F_o, it would also be an input signal, because it influences the liquid level, just as does F_i.

The point of all this is to look at a single schematic and know how to view it as a process, and as a system. View it as a process (F_o as an outlet stream) to write the material balance and make fluid mechanics calculations. View it as a system (F_o as an input) to analyze the dynamic behavior implied by that material balance and make control calculations.

System dynamics is an engineering science useful to mechanical, electrical, and chemical engineers, as well as others. This is because transient behavior, for all the variety of systems in nature and technology, can be described by a very few elements. To do our job well, we must understand more about system dynamics -- how systems behave in time. That is, we must be able to describe how important output variables react to arbitrary disturbances.

1.7 systems within systems

We call something a system and identify its inputs and outputs as a first step toward understanding, predicting, and influencing its behavior. In some cases it may help to determine some of the structure within the system boundaries; that is, if we identify some *component systems*. Each of these, of course, would have inputs and outputs, too.



Considering the relationship of these component systems, we recognize the existence of *intermediate variables* within a system. Neither inputs nor outputs of the main system, they connect the component systems. Intermediate variables may be useful in understanding and influencing overall system behavior.

1.8 the system of single-loop feedback control

When we add a controller to a process, we create a single time-varying system; however, it is useful to keep process and controller conceptually distinct as component systems. This is because a repertoire of relatively few control schemes (relationships between process and controller) suffices for myriad process applications. Using the terms we defined in Section 1.3, we represent a control scheme called *single-loop feedback control* in this fashion:

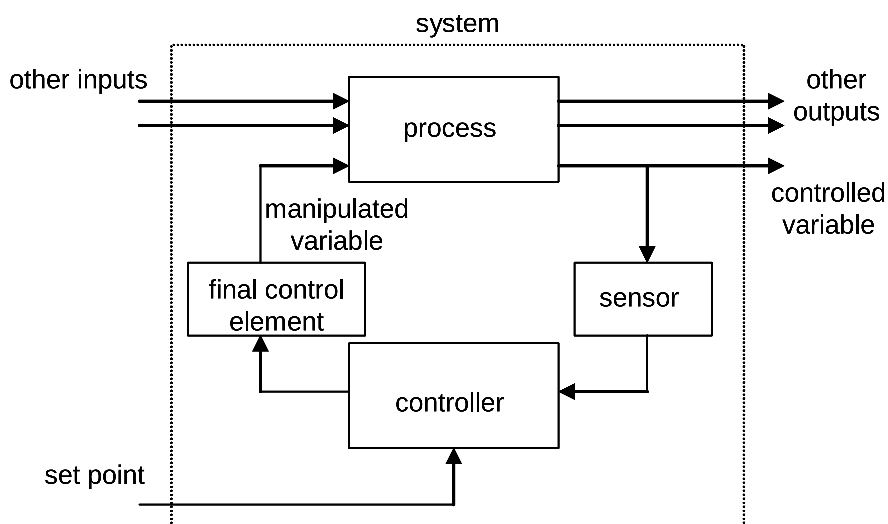


Figure 1.8-1 The single-loop feedback control system and its subsystems

We will see this structure repeatedly. Inside the block called "process" is the physical process, whatever it might be, and the block is the boundary we would draw if we were doing an overall material or energy balance. HOWEVER, we remember that the inputs and outputs are NOT necessarily the same as the material and energy streams that cross the process boundary. From among the outputs, we may select a controlled variable (often a pressure, temperature, flow rate, liquid level, or composition) and provide a suitable sensor to measure it. From the inputs, we choose a manipulated variable (often a flow rate) and install an appropriate final control element (often a valve). The measurement is fed to the controller, which decides how to adjust the manipulated variable to keep the controlled variable at the desired condition: the set point. The other inputs are potential disturbances that affect the controlled variable, and so require action by the controller.

1.9 conclusion

Think of a chemical process as a dynamic system that responds in particular ways to its inputs. We attach other dynamic systems (sensor, controller, etc.) to that process in a single-loop feedback structure and arrive at a new dynamic system that responds in different ways to the inputs. If we do our job well, it responds in better ways, so to justify all the trouble.