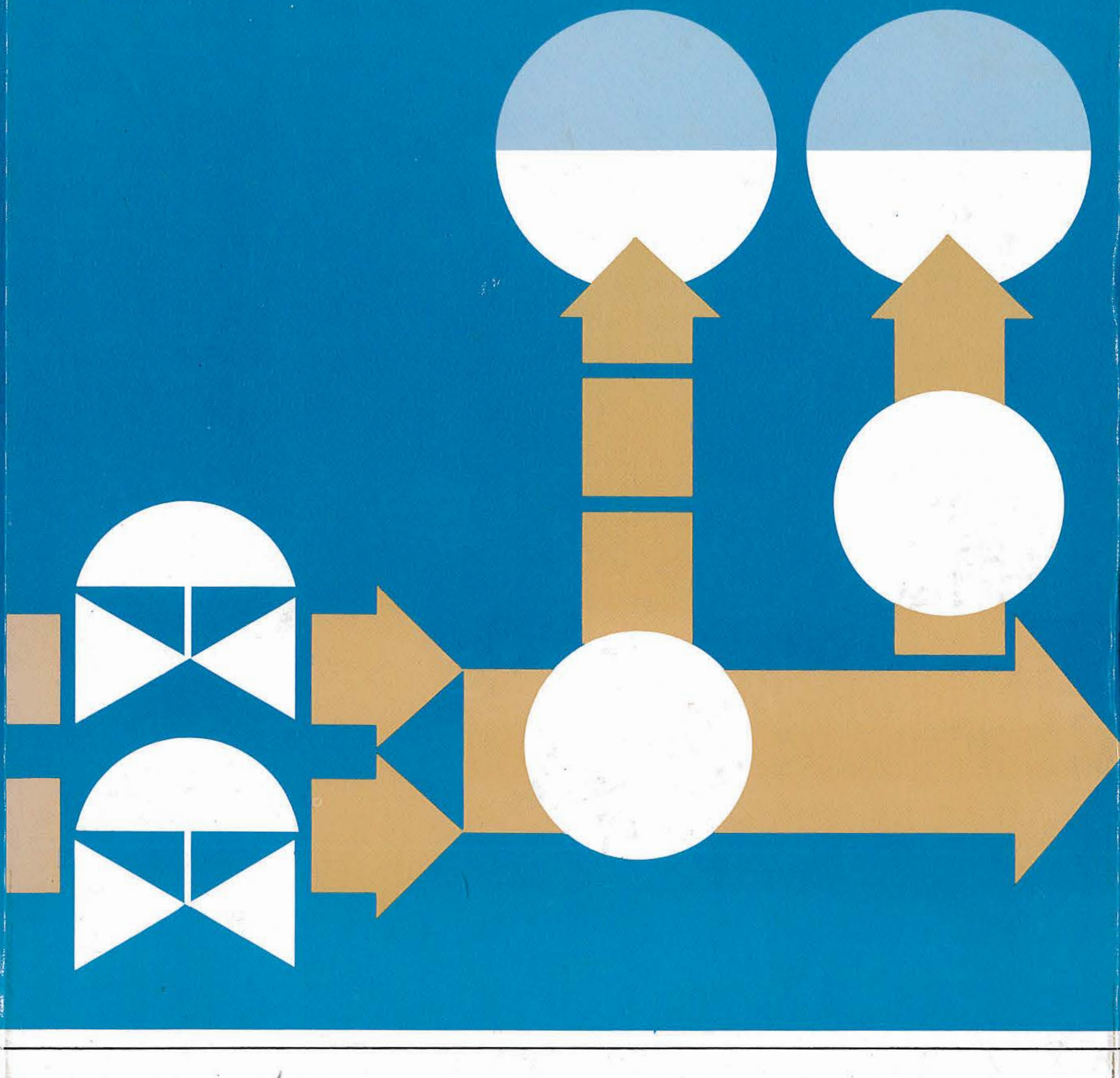
CONTROLLING MULTIVARIABLE PROCESSES

by F.G. Shinskey



An Independent Learning Module from the Instrument Society of America

CONTROLLING MULTIVARIABLE PROCESSES

By F. G. Shinskey

THE FOXBORO COMPANY
Foxboro, Massachusetts, U.S.A.

1981

INSTRUMENT SOCIETY OF AMERICA

3-7. Bidirectional Inventory Controls

Unit 2 addressed the location of the production-rate controller and the accommodation of constraints. Transfer of control to other limited manipulated variables was implemented by valve-position controllers. In this section, consideration is given to transfer of production-rate control serially from one process stage to another, with storage vessels between them. Inventory controls for the storage vessels must then be capable of manipulating either inflow or outflow, depending on whether the rate-controlling constraint is upstream or downstream.

Figure 3-7 describes a multistage process whose production rate can be set at either end or constrained at any intermediate operation. If product flow controller FC-3 is limiting, level will rise in tank 3, causing its high-level controller LC-3H to throttle its inflow. This action will raise level in tank 2 to cause LC-2H to act similarly, and LC-1H to manipulate feed rate.

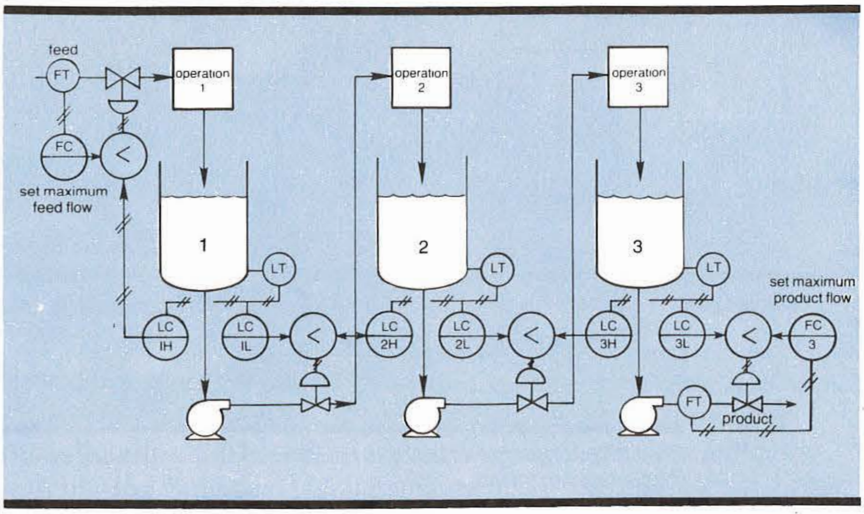


Fig. 3-7. Production rate can be set at either end of the process or constrained at any intermediate point without loss of inventory control.

Should the operator determine that feed rate is too high, he may reduce the setpoint of FC-1 below its measurement, causing FC-1 to take over feed manipulation. The subsequent reduction of inflow to tank 1 below outflow will cause its level to fall. Ultimately, its low-level controller LC-1L will react by taking control of outflow. This action will cause tank-2 level to fall, repeating the same scenario. Eventually a new steady state will be reached at the lower production rate and with lower levels in all tanks.

The system also accommodates constraints at intermediate points. Suppose a filter in operation 2 began to clog, reducing flow into tank 2. Its falling level would cause LC-2L and eventually LC-3L to manipulate downstream flows. Meanwhile, the level in tank 1 would rise, causing LC-1H to reduce the feed to match the rate of outflow.

If all level controllers have integral action, levels will come to rest at either their high or low setpoints, depending on the location of the flow limit. When the limit shifts its location, levels between the two locations will ramp from one setpoint to the other.

If all level controllers have proportional action alone, levels will reach a steady state that is proportional to the plant throughput. Another alternative would have proportional high-level controllers and proportional-plus-integral control of low level. Then levels will be proportional to throughput for vessels upstream of the flow limit and at the low-level setpoint for vessels downstream. With any of these choices, the tank capacities are used for buffering between operations, delaying the transmission of upsets in either direction. Momentary upsets in one operation might not interfere with adjacent operations at all.

Exercises

3-1. *Why is self-regulation a desirable property for a process to have?*

3-2. *Is the level of water in a boiler steam drum self-regulating? Explain.*

3-3. *What would make boiler steam pressure self-regulating? What would make it non self-regulating?*

3-4. *Add a surge tank to the process in Fig. 2-2 and arrange its controls so that the base level controller in the column does not have to manipulate its feed rate.*

3-5. *In what way does the system of Fig. 3-7 provide nonlinear level control?*

3-6. *Devise a bidirectional pressure-control system for a boiler supplying steam to a turbine.*

References

[1] Shinskey, F.G. *Process-Control Systems*, 2nd Ed. New York: McGraw-Hill Book Co., 1979, p. 20.

[2] *Ibid.*, pp. 116-118.

[3] *Ibid.*, pp. 253-257.

[4] *Ibid.*, pp. 134, 135.

Unit 4:
Environmental Variables

UNIT 4

Environmental Variables

This unit describes the control of the environmental conditions in which process operations take place and how the environmental variables may be adjusted to improve process performance.

Learning Objectives — When you have completed this unit, you should:

A. Recognize those conditions which affect process performance.

B. Be able to apply environmental controls to protect a process from disturbances in source and sink.

C. Understand how to adjust environmental variables to maximize process performance.

4-1. Relationship with Inventory Variables

Many of the variables which identified inventory in Unit 3 are also environmental variables, but not all of them. Environmental variables are distinguished by their effects on process performance. The temperature in a chemical reactor may represent an inventory of heat, but it also profoundly affects the rate of reaction. By contrast, the level of liquid in a storage tank may *only* represent inventory in that it has no effect on process performance.

The presence of self-regulation often identifies the environmental variables in that, as they change, they cause proportional changes in inflow and/or outflow. But environmental variables also affect product quality and the efficiencies of process equipment and machinery as well. In many instances, control over the process environment is sufficient to regulate product quality. In most cases, however, quality control requires that a particular relationship between the environmental variables and production rate be maintained. This is exemplified in a dryer, where air temperature is the environmental variable having the principal influence on product moisture. However, changes in production rate, feed moisture, and ambient humidity all require air temperature to change in a prescribed manner if product quality is to be controlled.

There is generally more than a single environmental variable which affects product quality—temperature, pressure, and composition all have their own influences. It then becomes possible to program these variables with respect to each other in such a way as to maintain product quality while improving process performance. For a reactor, this might amount to maximizing yield or catalyst life. For a separations unit, it would result in minimizing energy requirements. Each individual process needs to be examined to determine which of the variables that can be measured and controlled has the most pronounced effect on product quality, and how they can be coordinated to maximize efficiency.

4-2. Equilibrium vs. Nonequilibrium Conditions

Some processes require environmental controls over equilibrium conditions; in general, those processes have insignificant rates. Such is the case with material that is stored for extended times, as food in a freezer or paper in the process of being printed for instrument charts. Their environment largely determines their quality, but there is little transfer of material or energy between the product and its environment.

The same might seem to be the case for a room environment where people are at work, but there is a difference. People always radiate heat in proportion to their activity. Therefore, an environment where heavy work is being done needs to be cooler than a space where people are at rest. Even here, the quality of the product, which is comfort, is affected by how people dress as well as the environment. Then, there is an opportunity for optimization in the form of energy savings by adjusting the combination of clothing and temperature while keeping comfort constant.

Most processes operate in a nonequilibrium because production must take place at a definite rate. Environmental variables then become the rate-controlling mechanisms relating product quality and quantity. Temperature, pressure, and composition determine the rate of a chemical reaction, the rate of drying of a solid, the rate of heat and mass transfer in most processes. These are important considerations for the control engineer, for his system must be capable of controlling a process not only at design conditions, but also under all possible sets of conditions which may be imposed upon it.

Production rate is the most important concern because it can range from zero to full load, and can change virtually instantaneously. Feed composition tends to be limited to a narrower range and can change only as rapidly as source capacity will allow. Ambient conditions represent a significant set of disturbing variables to those units which reject heat into the atmosphere, e.g., refrigeration units, or draw feed from it, e.g., air compressors. Ambient variations can cover a full range of load for some processes like refrigeration and even span two distinct load ranges in the case of heating and air-conditioning. Separate systems required for the two distinct operating modes need careful coordination to minimize energy usage.

4-3. Reaction Conditions

The rate of a chemical reaction varies exponentially with temperature. This is true of competing reactions as well as the desired ones and of reactions involving degradation of the product as well as its formation. As a result, many performance criteria such as product quality, yield, and catalyst life depend on precise and responsive control of reactor temperature.

Endothermic reactors are highly self-regulating and therefore easy to control by the application of heat. Some exothermic reactors may be self-regulating, but most have negative self-regulation—presenting the possibility of a runaway reaction. Self-regulation depends on the heat of reaction, reactant concentrations, and the heat-removel mechanism. (An examination of reactor stability is beyond the scope of this work—for further information the reader is directed to Ref. 1.)

Temperature is a measure of the energy stored in the reactor and can be controlled either by heat input or heat removal. Heat input is directly proportional to reaction rate, which, in turn, is proportional to reactant concentration. If reactant concentration is very low or if the residence time is quite short, owing to a very fast reaction-rate coefficient, temperature can be controlled quite effectively by manipulating feed rate. This is not the normal loop arrangement, however, in that production rate would then be set by the rate of heat removal.

To avoid this problem, in some reactors temperature is controlled by introducing a diluent, which reduces reactant concentration and cools through sensible heat at the same time. Figure 4-1 describes a hydrocracker which is controlled by diluting the reaction mass with excess hydrogen. Inlet temperature is regulated at the feed heater—this is necessary to initiate the reaction. In a multiple-zone reactor, it is possible to optimize the temperature profile for the best combination of yield, production rate, and catalyst life.

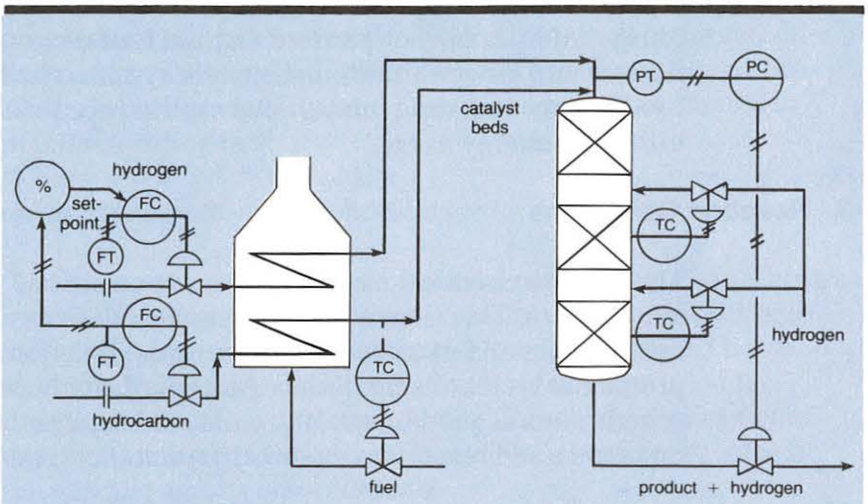


Fig. 4-1. Temperature is controlled at each of several zones in the hydrocracking reactor by dilution with cool hydrogen.

In many reactions, particularly those that function in the liquid phase, the residence time of the rate-controlling ingredient may be minutes rather than seconds. Then the response of reactor temperature to adjustments in feed rate is retarded by the intermediate step of altering reactant concentration. When the concentration time constant approaches or exceeds the thermal time constant, temperature control over feed rate become too slow for stable performance. This is especially true for reactors without backmixing. Then manipulation of heat removal is mandatory.

Figure 4-2 shows a jacketed reactor whose temperature is controlled by manipulating coolant exit temperature in cascade. For maximum stability, coolant must be continuously recirculated, with cold water added for temperature control. Hot water or steam is necessary for startup. The reactor temperature controller needs all three modes, while proportional or proportional-plus -derivative are preferred for the jacket controller.

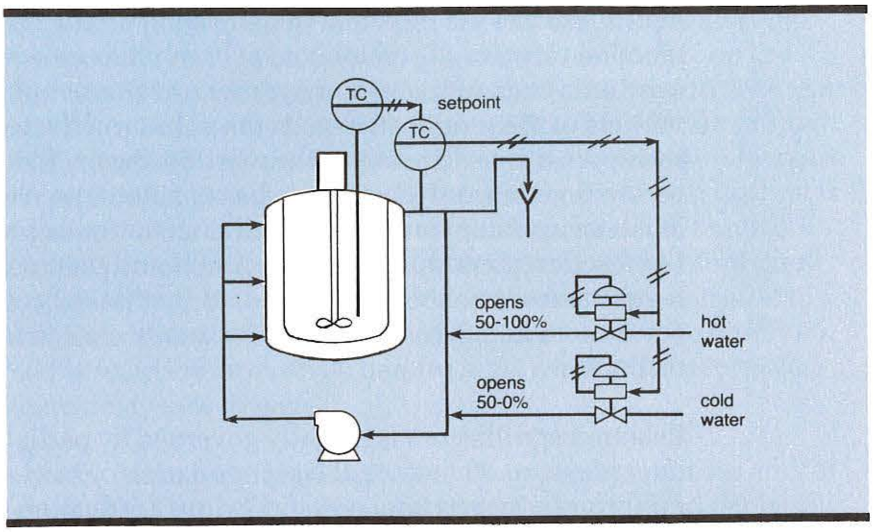


Fig. 4-2. Stirred-tank reactors need cascade control of recirculated cooling water for stable temperature regulation.

An even more stable heat-removal method is to boil water in the jacket as shown in Fig. 4-3. Then temperature is controlled by setting the jacket pressure, which determines the boiling temperature.

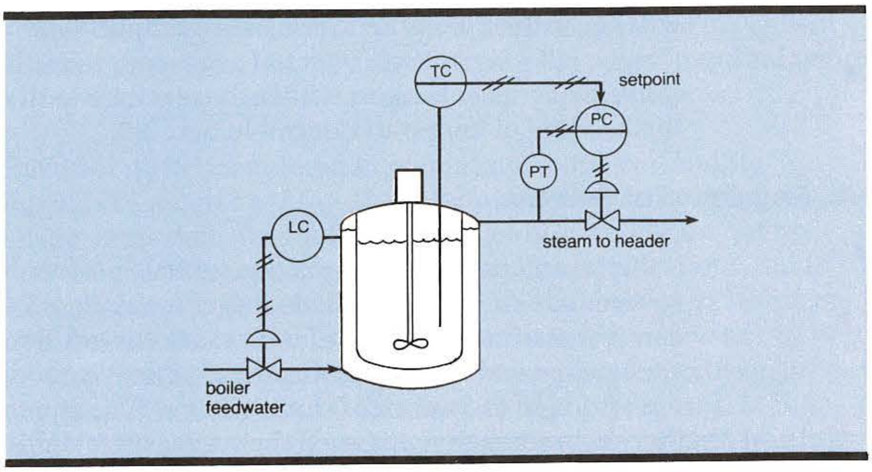


Fig. 4-3. A boiling coolant stabilizes an exothermic reactor by providing an isothermal heat sink.

Most reactions involving gases are sensitive to pressure as well as temperature. If the volume of the products is lower than the volume of the reactants, then increasing pressure will force the equilibrium in the direction of increasing production. These reactions are usually conducted at high pressure—ammonia synthesis from nitrogen and hydrogen is an example. If the volume of the products exceeds the volume of the feeds, then lower pressure will promote the reaction. Again, there are usually competing or serial reactions to be considered, such that there exists an optimum pressure as well as an optimum temperature. If the reaction is conducted in a boiling liquid then pressure and temperature may not be independent, so that only one need be controlled. In this case, pressure is usually chosen for its faster response.

Reaction equilibrium is actually governed by partial rather than total pressure. Therefore, the accumulation of inert gases in a mixture at constant total pressure brings a reduction in the partial pressure of the reactive gases. If it is necessary to control the conditions which determine reaction equilibrium, then partial pressure must be controlled. This can be implemented by controlling total pressure and concentration of the reactive gases, if a means is available for concentration control. If it is not, then partial pressure should be calculated by multiplying total pressure by mole fraction, and then controlled in the same way as total pressure. Then variation in the composition of the gas mixture will cause total pressure to rise or fall proportionately.

Control of concentrations within the reactor was discussed under the heading of Endpoint Control in Sec. 3-5.

4-4. Regulation of Sources

Material and energy are applied to various process units from sources which require some degree of regulation. Pumps and compressors usually are under pressure control, and heat-exchangers and furnaces are under temperature control. The regulation of the source of supply is crucial particularly when there is more than one user. If the source were rigidly regulated, then variations in demand by one user would not affect others at all. If it were unregulated, an increase in demand by one user would result in a proportional decrease in supply to all others to a degree based on the self-regulation of the source.

Consider what would happen if the source had no regulation of any kind, such as a positive-displacement pump supplying two users. A change in demand by one user would impose an equal and opposite change on the other. A centrifugal pump, on the other hand, has self-regulation in the relation of head to flow. An increase in flow to one user will decrease flow to the other through a reduction in head; but the lower head is the result of an increase in total flow, so that the second flow is reduced less than the first is increased. If the interaction is to minimized, pressure control must be provided. Even then, interaction may not be eliminated altogether, in that time is required for the pressure controller to function, during which a transient disturbance may be observed. Feedforward control can be helpful here, especially in furnaces, where delays are longer.

Pressure and temperature represent the inventory of mass and/or energy at the point of delivery between the supply and demand. But they are also environmental variables in that they affect the performance of both upstream and downstream processes. The temperature of the reactor feed in Fig. 4-1 determines the reaction rate, but it also impacts on the efficiency of the heater. Higher temperatures and longer residence times in the heater increase heat losses and degrade both the feedstock and the heater tubing.

The same is true of pressure controls on pumps and compressors. Higher discharge pressure and lower suction pressure may affect adjacent processes, but they also increase the power required per unit of throughput and the wear on mechanical components.

The difficulty encountered in regulating a source of supply depends as much on the quality of the source as it does on the nature of the demands. If fuel to a heater is of a constant quality, then the controls only need react to variations in demand. But if source quality such as fuel is variable, this too will have its effect on the controlled variable. If quality variations are slow to develop, feedback control over the environmental variable may be adequate. If not, the source may have to be compensated. In the case of fuel quality, compensation must be made for both heating value and density—in a function known as the Wobbe Index (2). The speed with which compensation is applied must be faster than the response of the process being upset—if not, compensation will be too late to be effective. Figure 4-4 shows a Wobbe Index analyzer being used to calculate the heat flow being delivered by a fuel valve. Note that the temperature controller sets heat flow rather than fuel flow.

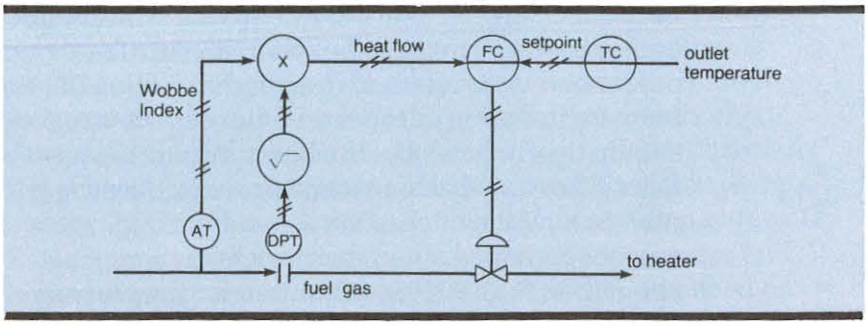


Fig. 4-4. Compensation for variations in source quality may be applied to the flow measurement.

4-5. Regulation of Sinks

The environment is our universal sink for both material and energy. It cannot be regulated, for its temperature, pressure, and composition are quite beyond our control. Yet there are various avenues through which material and energy are rejected into the environment, and these avenues frequently need regulation. Liquid wastes need to be treated by neutralization, oxidation, etc., and gaseous wastes need to be incinerated, scrubbed, etc. prior to discharge.

But there are far more point discharges of energy than material, and different avenues of heat rejection, such as river water, air, cooling towers, and refrigeration units. Isolation between the process and the environment is provided by a heat-transfer surface which presents a temperature difference proportional to heat flow. Furthermore, the temperature of the environment is variable. If process temperature or pressure is to be held constant, some means of control is necessary to adjust for the effects of variable heat flow and temperature of the coolant.

Dry atmospheric cooling is most variable because air temperature is most changeable, particularly in temperate climates. Wet atmospheric cooling is less variable because it is determined by ambient wet-bulb temperature which changes less than dry-bulb temperature. Surface water and groundwater are still less variable owing to the heat capacity of the earth. A refrigeration unit is a heat pump between the process and the environment, which, because of additional heat-transfer stages, becomes more variable than the environmental sink into which it discharges.

The difficulties encountered in regulating heat sinks is typified by the distillation column condenser shown in Fig. 4-5. Condensing temperature and therefore saturation pressure are determined by air temperature and the gradient across the heat-transfer surface. As air temperature and heat load change, saturation pressure will rise or fall, requiring an adjustment to the heat-transfer rate. The bypass valve accomplishes this by changing the amount of liquid held up in the condenser, thereby affecting the surface area available for condensing duty. Speed of response is relatively slow because liquid level within the condenser must change to affect the rate of condensation. Yet, because of its linearity and reasonably wide range, this is one of the preferred means of condenser control. Throttling coolant flow is nonlinear and promotes fouling; injecting noncondensible gas augments product losses.

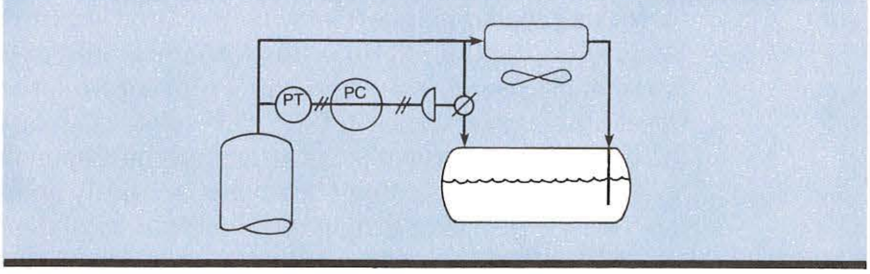


Fig. 4-5. The hot-vapor bypass valve reduces the rate of condensation by holding liquid in the condenser.

An important fact to realize is that the controls applied to regulate the heat sink need to be carefully matched to the characteristics of the sink. There are so many varieties, even of distillation column condensers, that they cannot even be mentioned here. For further information, the reader is directed to Ref. 3.

4-6. Optimizing Environmental Variables

Because environmental variables affect process performance, it is possible to program them to optimize performance. However, accomplishing process optimization is not easy—it requires an intimate knowledge of relationships between variables and the characteristics of plant equipment that its designers might not even have.

Optimization may take many forms. In some cases it involves simply setting the setpoint of a controller at some maximum or minimum limit, knowing that equipment constraints prevent operation beyond that point. In batch processes, optimization may require a particular program of a controlled variable, such as temperature as a function of time. Other variables may condition that function, however, such as initial temperature and concentration. Continuous processes frequently require programming of a controlled variable against an uncontrolled variable, such as temperature against concentration.

Sources and sinks generally are optimized at constraints which vary with flow rate and environmental conditions. Consider the air compressor supplying several users in Fig. 4-6. Discharge pressure should be minimized to save compressor power, but it must be high enough to satisfy the most demanding user. Demand is measured as the position of the user control valve. The most-open valve is selected for valve-position control at a setpoint of 90% or so. This allows a 10% control margin to accept increasing load changes. The valve-position controller must have integral-only action—proportional action would pass upsets from the selected user directly to the pressure controller and thereby upset other users. Closure of the valve-position loop depends on the action of the pressure controller and the response of the user flow controller in reacting to changes in supply pressure. Hence the VPC must be slower than the combination of those two loops, but will minimize energy consumption in the steady state.

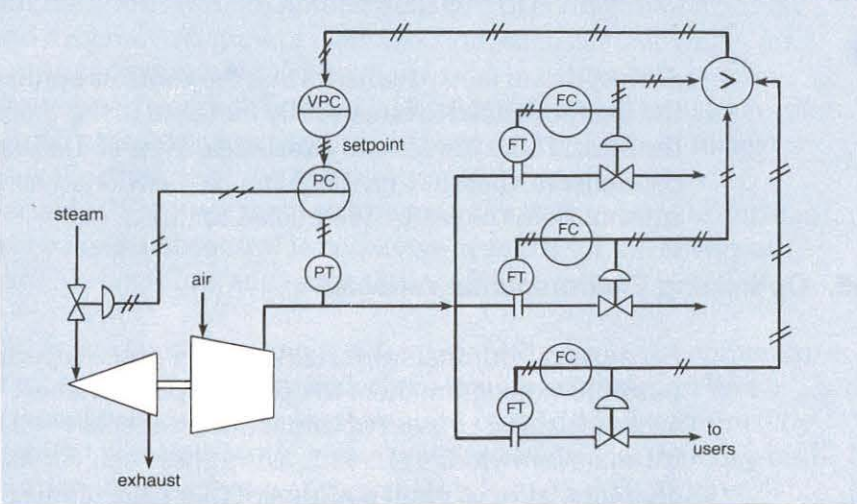


Fig. 4-6. The valve-position controller lowers pressure setpoint until the most-open valve is nearly wide open.

Figure 4-7 illustrates optimization of a heat sink for a distillation column. Most mixtures require less energy to separate by distillation as pressure and temperature are reduced (3). The lowest pressure at which the column can be controlled is that at which the bypass valve is nearly closed. The valve-position controller lowers the pressure setpoint until the valve is at its lowest controllable opening, e.g., about 10%. Its action must be very slow, with an integral time of about an hour, to allow the heat capacity of the column contents time to change to the new boiling point. Proportional action cannot be used.

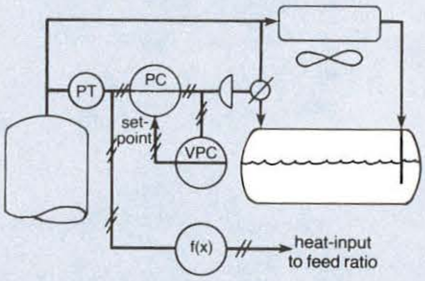


Fig. 4-7. The valve-position controller sets the pressure setpoint to its lowest controllable value.

Varying column pressure saves no energy by itself—it only will cause the purity of the products to improve. If energy is to be saved, heat input needs to be readjusted to maintain constant purity. This can be accomplished by product-quality controllers, but tends to be quite slow due to delays in product sampling and analysis. Response time is shortened by feeding the pressure signal forward to the heat-input controller through a linear function generator which is matched to the characteristics of the column. For further discussion on this application, see Ref. 3.

Exercises

4-1. *What makes a centrifugal pump self-regulating?*

4-2. *Why is a heat source necessary for an exothermic reactor?*

4-3. *Devise a system to control partial pressure of hydrogen at the inlet of the hydrocracker in Fig. 4-1.*

4-4. *Why is it necessary to control pressure in a distillation column?*

4-5. *When should an environmental variable be compensated for rather than controlled?*

4-6. *The temperature of hot oil used to heat a column reboiler is variable. How can a constant heat flow be obtained?*

4-7. *What variable(s) in a refrigeration system may be optimized to save energy?*

References

[1] Shinskey, F.G. *Process-Control Systems*, 2nd Ed. New York: McGraw-Hill Book Co., 1979, pp. 253-257.

[2] Shinskey, F.G. *Energy Conservation through Control*. New York: Academic Press, 1978, pp. 42, 43.

[3] Shinskey, F.G. *Distillation Control: for Productivity and Energy Conservation*. New York: McGraw-Hill Book Co., 1977, Ch. 7.