In small tanks, turbine mixers can also be used in place of mechanical pipeline mixers for continuous treating. If the turbine is run to discharge a large flow compared to the rate of feed, rapid and uniform mixing will result and the product can be withdrawn continuously.

Conclusion

The principles of mixing are now so well understood that it is possible to determine the fluid motion best suited for any specific process. Equipment can be selected that will give the desired motion most economically. In some processes pipeline mixing is sufficient and convenient. Most operations require intermixing of materials on both large and small scales and can be done best with propellers and turbines operating in tanks.

At all stages of the development of a new process, exploratory-research, bench-scale, and pilot-plant, attention to the mixing impeller and tank arrangement is necessary so that equivalent results can be reproduced in commercial sizes. When scale models of propellers and turbines are used, with well-known flow, turbulence, and power characteristics, the mixers can be selected with assurance. Otherwise the sizing of large-scale equipment becomes mainly conjecture and improvisation.

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Automatic Control

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ONE OF THE MOST SIGNIFICANT TRENDS in the chemical industry has been the continuous development of more and more complex automatic control systems. The modern chemical processing plant depends to a large extent on automatic controls for much of its efficiency. Present indications are that this trend toward more automatic systems will continue and at an accelerated rate. This is due in large part to the contributions made to development of basic control theory and control equipment during the last 10 years. Much of this development has been directed specifically at military applications, but fortunately the problems involved in aiming a gun at an enemy target are much the same as those encountered in setting a valve in a process line. Before discussing future developments however, it is best to review briefly some of the progress made in chemical process control and to establish in a general way the characteristics of a typical chemical process control system. This system can then be used as a basis for discussion of future trends.

Process Control Problems

Before discussing control systems in detail, it will be best to spend a little time discussing some of the problems which are peculiar to chemical processes.

A characteristic feature of a chemical process is the large amount of work done with fluids—gas, liquid, and even solid. In the latter case the solids are finely divided and supported in a gas or liquid stream. Usually one or more fluid streams enter the process, pass through a number of processing units, and then flow out as finished products. The processing units probably do one or more of three basic steps: heat or cool the fluid, subject the fluid to conditions such that chemical changes occur, or mix the fluid with another material. The most characteristic chemical control problems are found in the handling of flowing fluids. The usual control device (in fact, practically the only control device) used in a chemical plant is the valve. By opening and closing valves, materials may be rerouted through the processing steps or the speed at which they are moving may be changed.

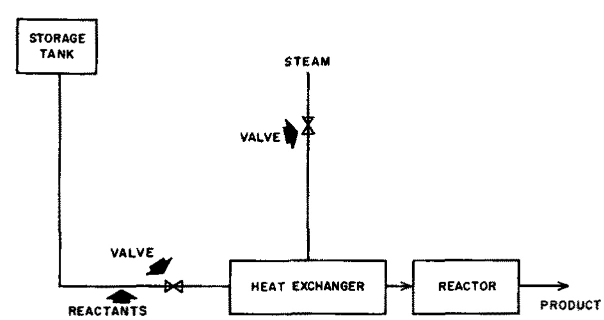

FIGURE 1

A typical chemical process is shown in Figure 1. The process is typical in that all the elements in it are common—not that such a process is often found in chemical plants. The process is described in some detail below because it will be used to illustrate the discussion of control systems given in the following sections.

The reactants are pumped from the storage tank, through the heat exchanger, and then through the reactor where a catalyst is used to increase the reaction rate. It will be assumed that the degree of reaction as measured by reactor effluent concentration is the critical product specification. The control agents which are available for changing the degree of reaction are the two valves, the one in the process flow stream and the other in the steam line to the heat exchanger. The factors which determine the settings of these valves can be listed as follows:

1. Changes in desired value of concentration in reactor effluent.

2. Changes in rate at which product is required. Short-term variations can be smoothed by providing a surge tank after the reactor. In the long run how-

ever a sustained change in demand means a change in flow rate through the reactor.

3. Changes in temperature or composition of fluid at inlet to heat exchanger. These might be caused by changes in the processes used to produce the raw materials, or changes in the conditions of storage.

4. The rate of heat transfer in the exchanger. This will change slowly with time and is caused by deposits of scale on exchanging surfaces.

5. Changes in catalyst activity. As the catalyst activity decreases, it will be necessary to use higher and higher temperatures to maintain the desired concentration in the product.

6. Other changes. Various other changes may occur which will have minor effects on the process. Although these effects are minor, they cannot be ignored, and some provision must be made for handling a random upset or change. Obviously, the relegation of effects to the "random" or "upset" category is entirely relative. All of the variables described above could be considered as of this type, and in the next section it will be seen that present methods of process control usually operate in this way.

Present Control Problems

The process described above in detail and shown in Figure 1 might be instrumented today as shown in Figure 2. Before discussing this control system in

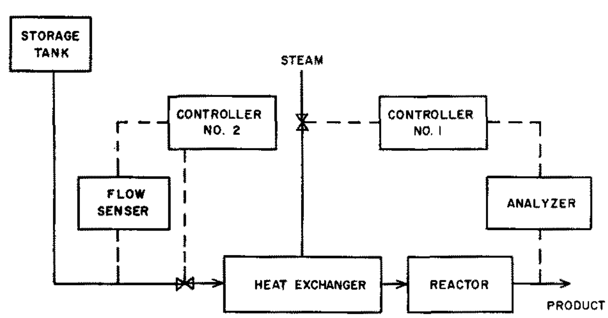

FIGURE 2

detail however, some general comments on present control methods are in order. Most chemical processes are operated at "steady state," that is, the goal of the instrumentation and control system is to maintain a certain number of key variables constant in time. To do this certain other process variables, the control agents (usually valve settings), are changed in some predetermined manner. A one-to-one correspondence is usually assumed between the controlled variable and the control agent. This is an oversimplification since interactions between various process variables are the rule rather than the exception. However if the process is maintained at near steady-state conditions, this control may be quite satisfactory.

The probability of operating at steady state for any length of time decreases rapidly as the complexity of the process increases. Hence most processes are divided into a number of smaller, simpler units, and each of these is operated as an entity. The connecting agent between units is usually the human operator. If a change in processing conditions is required, the operator does it manually. To assist the operator each unit is furnished with some extra capacity. In this way high frequency disturbances can be damped out, and only lower frequency changes need be handled by the operator.

The control system is normally an analog computer, operating on either a pneumatic or electrical analog of the process variables. Calculations are usually quite simple, being limited to multiplying the error by a constant (proportional action), integrating it with respect to time (reset action), and differentiating it with respect to time (derivative action).

Returning to Figure 2, is can be seen that two controllers have been used. Each controller is independent of the other. In operation the analyzer measures the composition in the reactor effluent stream, and then controller No. 1 opens or closes the steam valve in such a way as to maintain the desired concentration. If the rate of reaction rises above the desired value, then the valve will close. The heat input to the exchanger is reduced, and ultimately the reaction rate in the reactor will decrease. Similarly, an increase in reaction rate will result from opening of the steam valve. Controller No. 2 acts to keep the flow rate constant by opening or closing the valve in the process line. Each controller would probably have the usual proportional, reset, and derivative actions, and its action can be presented by

$$(1) \quad -V = \alpha\epsilon + \beta\frac{d\epsilon}{dt} + \gamma\int \epsilon \quad dt$$

where:

$V =$ Valve position, per cent.
$\epsilon =$ Error, actual value of variable minus desired value of variable.
$t =$ time.
$\alpha, \beta, \gamma =$ constants.

Knowing the characteristics of the controller and of the process and having some knowledge of the type of upsets to be expected, it should be possible to determine optimum values for the constants α, β, and γ for each controller. These optimum settings might also be determined by a trial and error procedure after the equipment is operating. The optimum settings however can only be valid over a rather limited range of process upsets. Such an elementary type of control as that described here could hardly be expected to handle any upset. Fortunately most of the changes with which the control system will have to deal will be in the range for which control action is satisfactory. If not, either the process or the instrumentation would be changed.

With this type of control any large change in operating conditions would be done by the operator. If, for example, a change in reactor outlet composition were desired, he would change the set-point and settings on the instrument and perhaps partially manually control the process until the new operating range has been reached. The operator might have available mechanical aids, such as graphic panels and automatic scanning and logging equipment.

This control system operates efficiently within certain limits. It is simple and economical; however it has several defects.

1. It takes no corrective action until an error has

occurred. The failure to recognize a need for control action until after an error occurs is particularly bad if the cause of the change and the means of applying the correction are separated from the measurement point by large capacities. In fact, a particular type of separation called dead time or distance velocity lag is very difficult to control. Dead time occurs in that part of a process in which a finite time length is required for the measuring device to note any change.

2. The controller assumes a simple one-to-one correspondence or cause-and-effect relationship between the controlled variable and the control agent. In the process discussed above, if it is assumed that the desired flow rate is determined by conditions outside the process, then the only means of varying the reaction rate is the steam valve. In this case each of the process variables discussed previously (concentration of reactor effluent, flow rate, reactant conditions, heat transfer rate in the exchanger, and catalyst activity) is a factor in determining the correct steam valve position, but Controller No. 1 in Figure 2 uses only the concentration in its control section.

3. The controller is capable of only the simplest kind of calculation, such as that given by equation 1. Its inability to solve more complex equations is basically the reason for items 1 and 2 above. When the error is small, equation 1 is satisfactory, but it can hardly be expected that the constants α, β, and γ are independent of error and independent of the set-point from which the error is calculated. For example, if a change in heat exchanger inlet temperature, Ti, occurs at constant flow rate for the process of Figure 1, the change in valve setting required can be shown to be:

$$(2) \quad -dV = \left[\frac{K_V}{T_f - T_i} + \frac{P_s \lambda}{2RT_s^2 \, (P_i - P_s) \quad (e^{UA/MC_a} - 1)} \right] dT_i$$

where:

V = Value position, per cent.
T_i = Temperature of reactants entering heat exchanger.
T_f = Temperature of reactants leaving heat exchanger.
T_s = Temperature of steam saturated at P_s.
P_s = Pressure of steam in heat exchanger.
P_i = Pressure of steam before passing through steam control valve.
U = Heat transfer coefficient in heat exchanger.
M = Flow rate of reactants.
C_a = Average heat capacity of reactants.
A = Area in heat exchanger available for heat transfer.
λ = Latent heat of steam at P_s.
R = Gas constant, 1.98 B.T.U./(lb. mole) (°Rankine).
K_V = A valve constant.

The assumptions and calculations involved in the derivation of equation 2 are not of interest here. It is important however to see that the correct *steady state* relationship between valve position and inlet temperature is a complicated expression. It should also be noted that this equation is valid only after all transients have died out. During the period of change even more complex equations are required. For example, if a decrease in inlet temperature occurred, it would probably be desirable initially to open the steam valve more than required by equation 2, then close it to a lower value, and then slowly cycle with decreasing amplitude until the steady state is reached.

Returning to the steady state equation, if changes in inlet temperature are small and if other variables such as flow rate are constant, then the quantity in parentheses can be considered as a constant. The valve position would then be proportional to inlet temperature, and equation 1 could be modified to:

$$(3) \quad -V = \alpha\epsilon + \beta \, d\epsilon/dt + \gamma \int \epsilon dt + a_1 Ti$$

This is sometimes done in modern control systems and is known as anticipation control or cascade control (1). To provide better control during the period of change to a new inlet temperature, it might be desirable to include the derivative of Ti with time in equation 3 also. In any event, the use of an expression such as equation 3 is at best an approximation which holds over a rather limited range of operating conditions. It would be desirable to have controllers capable of solving more complex expressions where necessary.

Future Trends in Chemical Process Control

The process discussed above is only a single unit in a more complex process, but at least as far as the control system is concerned, it is treated as being independent of the rest of the process. This is typical of chemical processes. They are usually subdivided into a number of more or less independent units, each of which has its own instrumentation. In each unit the instrumentation is normally designed to maintain steady-state operating conditions. Coordination between units is done by human operators.

It seems likely that future trends in chemical process control will be primarily to consolidate the present multiplicity of independently controlled units into a single completely controlled process. A change in any part of a plant will be automatically recognized by the control system and the appropriate action taken. As a result, the human operator will be needed less and less for routine control because changes resulting from new production requirements or operating conditions will be made by the control system. The transition to a more unified control system will have to take into account the following factors:

1. *Interaction Between Process Variables.* The present tendency to use only one process variable for each control agent is not suitable for really complete control. It will be necessary to develop more thoroughly the relations between important variables in chemical processes and utilize as much information as necessary to get the desired control. Equation 2 gives a good example of such a relationship for a very simple process. Although it is complex, it is simpler than those found in most actual processes. On the other hand, it is unlikely that anything as complicated as equation 2 would ever be solved in the form given. The main usefulness of such an approach is that it points out which variables are important and how they affect the proper setting of the various control agents.

2. *Transient Behavior of Chemical Processes.* Relatively little is known about the transient or unsteady state behavior of chemical processes. One result of this has been the emphasis on steady state operation of processes. It is not only impossible to operate for very long at steady state, but it is not usually desirable because changes in production requirements, raw materials, economic factors, and processing equipment and techniques occur continually. Although little work has been done on the transient behavior of chemical processes, interest in this subject is increasing rapidly. Although much work is being done (2), more is needed.

3. *Optimization of Chemical Processes.* The availability of large computing devices has opened up new possibilities in the analysis and planning of industrial operations. Through the use of such techniques as linear programming and statistical correlations it is possible to take into account economic factors, production requirements, equipment performance, and even make allowance for the effect of competitors' strategy (3). These methods can remove much of the uncertainty and even guesswork that have gone into some of these decisions in the past. They also make it more and more important that the process be flexible enough to respond to changes as required. It may some day be possible to give a computer such economic information as is necessary, have it compute the optimum operating conditions, and then make the appropriate changes in process control points.

4. *Need for New and Better Control Systems.* It should be evident from the preceding discussion that new control systems will have to be devised. Whether they can be obtained by extension of present control systems or whether new concepts will have to be developed is difficult to say. It is possible to predict however that a system capable of controlling a process as described above will have to solve relatively complex equations, take into account several variables in determining each process control setting, be able to have its control section modified or changed completely in a short time, and be able to accept instructions from such varied sources as computers and human operators. In addition, the control system should be accurate, dependable, and as cheap as possible.

Some of these points can be illustrated by examining Figure 3 which shows how the process discussed

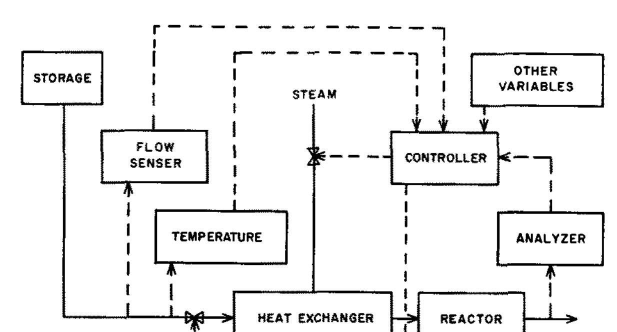

FIGURE 3

previously might be controlled. The controller analyzes four sources of information in determining the two valve positions. These are the product concentration, the flow rate, the heat exchanger inlet temperature, and any other variables from outside the process. This latter category would include the desired values of the variables. To change any quantity it would only be necessary to send the information to the controller, probably as an electrical signal. The controller takes all four inputs, performs any needed calculations, and then opens or closes each valve. The action is, of course, continuous in time.

It is evident that if the controller is properly set and is capable of performing the necessary calculations, it is possible to keep the process under almost perfect control at all times. Further the process will be flexible and able to shift from one level of operation to another with no interruption in product quality. The chief difficulty here is properly adjusting the controller. Admittedly that would be difficult, but it is not impossible.

New Developments in Controllers

Discussion until now has been centered primarily on what controllers should do. It is now in order to outline briefly just how the requirements in (4) above might be met. To begin with, it should be noted that any controller action can be expressed as an equation, and therefore a controller can be considered as a computer or, conversely, a computer can be used as a controller. There have been advances in computing devices in the last 10 years, and it seems almost certain that the controllers of the future will develop from present computing techniques. In analyzing the controller duties, it is convenient to divide them into two groups, those duties that involve the making of decisions and those that do not. The ability to make decisions will be called "executive ability" in the following discussion and is a vital part of the over-all control problem. Any attempt to determine optimum operating conditions or to evaluate alternative processing schemes must involve the making of decisions. This executive ability is normally achieved only in the more complex computers and is necessary if human operators are to be relieved of many of their duties. The non-decision making calculations are simpler, and less complicated computers can be used. It seems reasonable to predict that the automatic control system of the future will have two kinds of controllers, simple ones to perform the routine calculations and more complex ones for the more difficult control applications. In essence, the more advanced computers will be used to coordinate the operation of the simpler controllers. In considering the type of controllers which will be used for each application, it is convenient to divide controllers into two groups, analog and digital.

Analog Controllers. These computers represent the variables in the equations by continuous physical quantities. Most controllers used today in chemical plants are simple analog computers which use air pressure or electrical voltage or current as the analog quantities. Electrical analog methods are used almost exclusively in more complicated problems, and it seems almost certain that the analog controllers of the future will be electrical. Much work has been done in the development of complex analog controllers for military uses, and the same principles can be applied to chemical process problems. There is no question but that analog controllers can be designed today which will satisfactorily serve as non-decision making controllers. Some executive ability can also be built in, but it does not seem likely that analog controllers can be used for some of the very complicated optimization techniques now being applied to chemical processes—for example, linear programming problems which involve the repeated solution of large sets of simultaneous equations.

Digital Controllers. These computers operate only on numbers. A desk calculator is a simple digital computer. Decision-making is an important function in large digital computers, and they are currently being used for the solution of problems involving the optimum over-all operation of chemical plants. For executive control applications, then, digital techniques are well developed. Although digital computers have not been used often for the simpler control problems (primarily because of greater cost and relative newness), it seems quite probable that they will be used in the future. Special-purpose computers for control applications will be developed and should be cheaper than present general purpose computers. Some of the advantages of digital controllers are:

1. Ability to perform complex calculations and generate non-linear functions. Digital computers can perform any calculation, but, of course, the more difficult the calculation, the larger the computer must be.

2. Ability to perform complex calculations with constant accuracy. Digital computers can have any desired degree of accuracy in calculations at relatively little increase in cost. The cost of analog computers on the other hand increases rapidly as the complexity of the calculation increases if constant accuracy is to be maintained.

3. Ease of programming. The principle of stored programs makes the digital computer or controller an extremely versatile instrument. By merely issuing a new program, consisting of a sequence of numbers, the operations being performed can be completely changed. This feature is particularly important if the control system is to receive operating information or instructions from some computing center where economic analysis and optimization studies are being made.

Summary

Although the chemical industry makes extensive use of automatic controls now, it seems likely that the trend to more automatic control systems will continue until eventually the completely automatic plant will be developed. An analysis of present methods with this ultimate goal in mind indicates that the following developments will take place:

1. Abandonment of the present practice of using only one process measurement to determine the setting of a control valve. The correct setting for a control point is usually determined by several process measurements.

2. Unification of individual units in chemical plants. Because of the inability of present control systems adequately to handle complex control problems, it has been customary to subdivide a process into smaller units and handle each of these as a separate control problem. Human operators are normally used to coordinate the operation of units.

3. Inclusion of optimization techniques in this control system. Recent developments in large-scale computers and mathematical methods provide the basis for use of all available information in the control system. This part of the control loop is currently being done by humans.

In order to provide control systems capable of performing the operations listed above, new controllers must be developed. In addition to being accurate and dependable they must perform several functions.

1. Be able to handle many inputs and outputs. Interactions between process variables must be taken into account in each control action. This means that each input affects several outputs, and conversely each output is determined by several inputs.

2. Be capable of making complex calculations. The more complete the control, the more important it is that the correct relations between operating variables be known and used. These relations are normally quite complex.

3. Be so designed that its control actions can be easily modified or changed during operation. To obtain maximum benefit from optimization procedures, the control system must be versatile enough to accept changes during operation.

The actual controllers which will be used will develop from present computing and control devices. It seems likely that the complete control system of the future will consist of a digital computer or controller for over-all decision or executive control which will have under its supervision smaller analog or special purpose digital controllers for the routine control problems.

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