CHAPTER II

GENERAL PRINCIPLES AND STRUCTURES IN BOILER CONTROLS

The entire steam generation process may be modeled in great detail by breaking the flow path into finite volume sections, and solving for the variables at the boundaries of the sections using the mass balance, energy balance, pressure drop, heat transfer equations as listed in Fig. 1.15 of Chapter I.

A natural boundary in the process physics is the tube metal which separates the gas path from the water and steam fluid path. The coupling between the two processes is the metal temperature which integrates up or down as a function of the difference between heat transfer from gas to metal and from metal to fluid.

The techniques of model development from first principles are covered in Chapter XII.

While this approach is desirable and necessary in many situations, especially in modeling of once-through boilers, a great deal of insight may be derived from simplified models that define the response of primary output variables to those input variables which have a dominant effect. Examples of several of these simplified models are illustrated in following chapters along with single loop control configurations defining the dominant control actions.

Wherever possible we shall develop a sense of appreciation for sound control principles illustrated by examples.

The job of designing a system to perform a given control task usually involves a choice among a number of ways to accomplish the control function. The selection of the best way requires use of judgement in deciding to what extent concepts such as feedforward, feedback and adaptive control should be applied. By sound judgement we imply proper recognition and use of basic guiding principles that should influence control design.1 Some of these principles are:

1. Simplicity

Among various systems that perform equally well, the best is usually the one that has the fewest components and need for least number of adjustments.

2. Use of Process Intelligence for Control

Strong use of actual feedback from process information wherever possible gives actual rather than inferential information to the control system.

In a situation where the control function can be accomplished well by feedback, additional use of feedforward requires that the action from feedback be reduced to prevent overshoot. Since feedforward
action can only account for a few measured disturbances, this means that system performance will suffer for the cases of unmeasured upsets.

3. Need for Adaptive Features

It is inherent that the need for adaptive or self-calibrating features is much greater in systems that rely heavily on feedforward action. The use of feedback wherever process dynamics permit provides a great degree of adaptation in ways that are more subtle and less apparent than in systems with a liberal number of multipliers modifying feedforward action. Feedback by its very nature minimizes the effects of changes in process parameters.

4. Stability of Controls

Taking full advantage of process information in control configurations gives rise to closed loops and care and sophistication must be exercised in dynamic shaping of control action. Not only must the controls have the proper proportional, reset and rate action for the linear (small perturbation) mode of operation, but they must provide for smooth transition in and out of nonlinear ranges of operation when components or equipment go into limits or saturation.

Although the boiler process is multivariable, and, strictly speaking, control of inputs can be conceptually visualized as directed by a matrix from process outputs (Fig. 1.4), it is logical to compose the controls from basic primary loops relating certain process variables and the inputs that have dominant effects on these variables. Additional coordination or cross coupling between loops is then superposed as needed.

A review of some control concepts as applied in the boiler control area is appropriate prior to discussion of specific applications.

**PROPORTIONAL FEEDFORWARD CONTROL**

Proportional feedforward control is described in Fig. 2.1 as the most elementary form of open-loop control.

This concept has been used in large measure usually in combination with other forms of control and has been attractive because of its apparent simplicity. It is also attractive due to the fact that it does not give rise to stability problems as may arise with closed-loop feedback systems, and in days past when feedback control was a relatively mysterious field (pre World War II) and hardware was not available to give proper dynamic compensation and to prevent such things as reset windup, it is understandable that the industry relied heavily on this concept of control.
The basic idea is that using one fundamental signal indicative of the demand from the process, one could position all necessary inputs in feedforward open-loop fashion. Of course, this works well in elementary types of systems, but is by itself entirely inadequate in boiler control for the following reasons:

Calibration - The boiler process is complex, nonlinear and is influenced by several factors in addition to the fundamental load demand. These factors are usually unmeasurable. The instrumentation technician would have to spend a career calibrating the system, characterizing cams, etc., and would still find performance unsatisfactory because of accuracy and dynamics. Accuracy because even with the best possible characterization, the control requirements are much too stringent for this type of control by itself to be effective. For instance, in a once-thru unit, a 1% error in the required amount of fuel would result in a steam temperature deviation of 17°.

The other serious shortcoming of this simple proportional feedforward system is the absence of dynamic shaping of control action. Due to the complex and high order storage lags in the process and the interacting nature of the variables, proper control action must often undergo rather involved trajectories in time when taking the process from one state to another. The oversimplification of forcing the process inputs instantaneously from one steady-state value to another in response to a step change in demand can sometimes result in large transient deviations of critical variables.
A homey analogy of the inadequacies of this control concept can be found in the example of trying to help the job of backing a trailer from one position to another by instantly positioning the car's steering wheel to its expected final value!

We can trace the next step in the evolution of control configurations used in boiler controls to that shown in Fig. 2.2.

![Diagram of control configuration](image)

**FIGURE 2.2**

Here we have still kept as the primary control the proportional feedforward action previously discussed but have added a feedback trimming action from a relatively slow reset, proportional + reset, or sometimes proportional + reset + rate control operating on the error of the basic process variable.

This concept is often useful but has been misapplied. One area of misapplication has been where process dynamics are complex enough to invalidate the effectiveness of a simple proportional feedforward signal, as previously described. An example is proportional anticipation of feedwater demand from steam flow. Having this anticipation as instantaneous can add to the drum level swell effects.

The other case is where the process dynamics are fast enough making the configuration with feedback only, with the error operating on a reset, two mode, or three mode controller entirely adequate. In these cases where the process dynamics are fast, addition of feedforward, as in Fig. 2, requires detuning or slowing down of the feedback action to avoid overcontrol and consequent overshoot. Detuning of feedback control deteriorates the performance of the control system under disturbances other than the primary disturbance from which feedforward action is provided.
Fig. 2.4 exhibits examples of the open-loop step response characteristics of such processes normalized to have the same final value of unity.

\[
A = M_0 = \int_0^\infty (1 - f(t))dt
\]

\[
M_1 = \int_0^\infty t(1 - f(t))dt
\]

\[
C = \frac{M_1}{M_0} = 1.0 \quad C = 0.85 \quad C = 0.65 \quad C = 0.5
\]

**FIGURE 2.4**

At the extreme left, we have a first order lag or single time constant system. Progressively higher order lag systems are shown in the successive response traces until reaching the extreme case of a pure dead time system at the extreme right. The controllability of these systems deteriorates with the increasing order of the lags.

Without resorting to traditional frequency response or S-plane analyses, one relative measure of the controllability of these processes is to characterize them by a dimensionless ratio of the moment of the area A (see Fig. 2.4) about the t = 0 axis to the area A squared. (Note that area A, also called loss area, is the zero order moment of the function \(1 - f(t)\) where the \(n^{th}\) moment of that function is defined as \(M_n = \int_0^\infty t^n (1 - f(t)) dt\).
One obvious conclusion is that if the system with feedback only is effective from a response standpoint for both the primary process disturbance as well as for other disturbances, then it is the preferable system both from a performance as well as from reliability and ease-of-adjustment points of view. One of the fundamental axioms of good control design is "simplicity".

**FEEDBACK CONTROL**

A most important area concerns control modes in feedback configurations, as shown in Fig. 2.3. In discussing this configuration it is appropriate to note that the response characteristics of the process dictate the combination and amount of control modes which should be used for greatest effectiveness. Some of these modes, proportional, integral, and derivative (rate), are discussed in Appendix F.

![Figure 2.3: Feedback Control Diagram](image)

**FIGURE 2.3**

In examining the control needs in feedback configurations, it is helpful to relate these to the particular process dynamics. Let us examine first a wide range of processes whose open-loop responses can be characterized by various orders of lags (i.e., a process with no zeros or complex poles but with varying number of real poles).
The dimensionless figure of merit $C = \frac{M_1}{M_0^{1/2}}$ or $\frac{M_1}{A^{1/2}}$ has the time dimension scaled out of it and is purely a function of the shape of the response curve.

The class of processes, shown on Fig. 2.4 has this figure of merit, $C = \frac{M_1}{M_0^{1/2}}$, ranging from a minimum value of 0.5 for a pure dead time case at the extreme right of Fig. 2.4 to 1.0 for a single time constant system shown at the far left of the same figure.

A common misconception in this industry has been that proportional control is always easiest to apply and that integral control is harmful from a stability standpoint.

Analysis of the control characteristics required for a particular process shows that the dead time process, or the process with multiple order lags, cannot stand a high proportional gain. In fact, a gain of less than unity is required for stability in the case of a pure dead time system. In such processes integral action is necessary to produce the proper attenuation with increasing frequency so that the open-loop gain drops below unity before the phase lag of the process becomes excessive.

It is important to note that over a wide range of values of $C$, especially where the process has some dead time, the acceptable value of proportional gain is so low that proportional control only would be almost as good as no control at all! (A proportional gain of 1.0 would allow an error between demand and feedback of 50% - a proportional gain of 0.2 would allow an error of 83%).

High proportional gains are only applicable in the control of low order lag systems, but unfortunately these low order systems are not as universal as might first appear from a survey of academic papers on control analysis.

Beside the commonly occurring processes, whose response characteristics are described in Fig. 2.4, there are those where the system open-loop function has zeros in addition to high order poles. Fig. 2.5 shows an example of the response of one such system encountered in the control of air flow with changes of fan speed through a hydraulic coupling.

**FIGURE 2.5**

Response of air flow to step change in signal to fan coupling
response trace of air flow to a change in signal to coupling exhibits a dead time, even if
is lag followed by an overshoot which is due to the charging of the boiler volume. An
pure integral controller with very little proportional action is indicated for this type of
process.

The control of feedwater flow through changes in the turbine driven feed pump speed exhibits
similar requirements, i.e., pure reset action and zero proportional gain. The universal applicability
of proportional control as the first step in control is, therefore, invalid.

CASCADE CONTROLS

The principle of cascade control, as illustrated in Fig. 2.6 is widely used in boiler controls.
Some limited degree of cross coupling between loops is also used.

![Diagram of cascade control system]

**FIGURE 2.6**

The advantage of cascade control arrangements is that they linearize the process through use
of subloops. These subloops also automatically compensate for disturbances as they occur through
intermediate stages of the process without having to wait for the effect of the disturbances felt
in the main process variable.