

a relatively easy process to control since no time lags are present. A more difficult process requires careful adjustment of the instrument to attain stability.

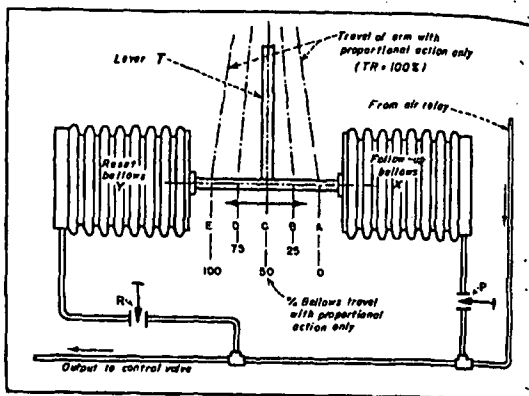
Thermal Lag. Assume the left-hand tank represents heat inflow or steam input to an air-heating coil. Water flow from the tank now represents heat flowing through the coil wall. By imposing a restriction to water flow from the first tank we can simulate resistance to heat flow through the pipe wall, (thermal lag). To provide this restriction, a small hole is drilled in gate of valve between the two tanks. With valve closed, water flow is restricted to the small opening. Right-hand tank represents temperature level of surrounding air, and it is this level we wish to control.

Closing the gate valve introduces time lag in system, and left-hand tank level begins to rise because of restricted outflow. We now visualize continued inflow of steam to the coil (first tank), but because of thermal resistance (small hole in valve), heat is delivered slowly to surrounding air (second tank). With continued addition of steam, temperature level of air (water in second tank) rises enough to cause the controller to close the supply valve. Level in left-hand tank is still abnormally high and because of the time lag, it recedes slowly. Excess water in this tank corresponds to heat stored in the walls of a heating coil when supplied with too much steam.

As air temperature gradually drops (level in second tank), the controller again comes into action to open the valve. Cycle then repeats because the valve tends to overshoot desired flow rate necessary for stable operation. The cyclic condition may continue indefinitely and at best requires considerable time to dampen out. We can conclude that the throttling range of the instrument must be increased to stabilize the system.

Effects on Offset. Increasing the throttling range also increases amount of offset from the control point experienced with a load change, so we need automatic load-change compensation. Before designing such automatic compensation, let's investigate operation of a proportional controller having 100% throttling range when the load changes.

Making necessary adjustments, we set the petcocks for 50% load. Output pressure settles out at 9 psi and the process reaches stable condition. With 9-psi output pressure, lever T, Fig. 4, is in its midposition since movement of bellows and spring mechanism is proportional over a range of 3- to 15-psi



5 Two opposed bellows connecting to nozzle arm gives both proportioning and reset action if restricting valve to bellows Y is adjusted to match the process needs

output pressure. Remember when the pen is at midpoint, the baffle is at its midpoint, and output is at midpoint of its range. Consequently, lever T is at its midpoint of travel, and thus the nozzle is correctly positioned in relation to baffle. With a change in pen position, all the foregoing parts move in proportion to magnitude of change.

If we change the process load to 75%, the float drops, pen moves up scale, and as the controller mechanism gradually reaches a new point of balance, output pressure reaches 12 psi. Control valve now passes a flow equivalent to 75% load and the process is again in balance. Examination shows that lever T has moved to the left and now occupies a position corresponding to 75% of its total travel.

Seeking some way to return the process to its original control point and still maintain balance at 75% load, we first analyze the condition of the process. It is evident that tank level is below the desired control point, so the valve must be opened farther to admit more water. To do this we must increase the output air pressure.

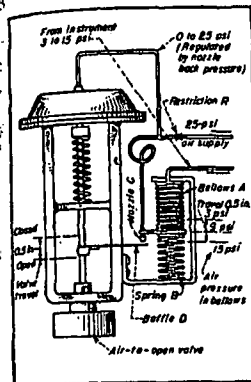
By disturbing the nozzle-baffle clearance the amplifying action of the relay produces the desired increase. Compressing bellows X to cause such a disturbance returns lever T to its original midposition. Output air pressure immediately increases, controlled valve opens, and tank level rises to its original position. Pen has now returned to the desired control point.

If repositioning of lever T needed the application of an external force to the bellows and spring unit in a direction to further oppose bellows action, and the load change experienced caused an increase in output from 9 to 12 psi, an auxiliary bellows, so placed to oppose bellows X, would supply the needed external force if the 3-psi change were utilized as the restoring power. Let's investigate replacing the spring with a bellows.

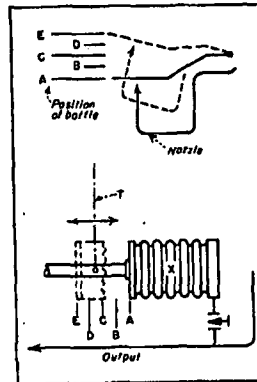
Referring to Fig. 5, bellows Y replaces the spring and opposes bellows X. If Y is to furnish an opposing force equal to the spring a given amount of air must be trapped within it. At a starting point, let's charge the bellows with normal output pressure of 9 psi required by the controller to maintain stable control at 50% load and close valve R.

After adjusting link S to compensate for a slight variation between spring and inflated bellows, the controller reproduces the 100% proportioning action obtained with the spring-opposed bellows. This action can be checked by moving pen, Fig. 3, across chart and observing the proportional change of output pressure.

Eliminating Offset. Allowing the process to reach stable control at 50% load, we now increase the load to 75%. As with the previous controller, as the pen moves to 75, output pressure gradually reaches 12 psi and lever T moves to the 75% position. We now want to return lever T to its midposition and thereby upset the nozzle-baffle relation-



6 Nozzle-baffle system mounted on valve positions the stem accurately



7 Nozzle position, determined by lever T, controls output pressure, Table I

ship to rebalance the system. By opening valve R, Fig. 5, we can admit output air at 12 psi into bellows Y and force lever T to its midposition. At this point both bellows Y and X are charged with 12-psi pressure and reach a position of equilibrium just as they were when equally charged with 9-psi pressure. In both cases, lever T is at its midposition. Table II shows this stepwise reset action.

The process has rebalanced during this procedure and the pen has returned to the control point within the color band. As we observe the process action, controller appears to behave like an on-off unit. Process has fallen into a cyclic state and pen continues to surge first above and then below the desired control point (color band).

Reason for the on-off behavior is obvious as we watch opposing bellows Y work, Fig. 5. With valve R fully open, both bellows receive an equal impulse from the output line. So no motion is imparted to lever T to cause proportioning or follow-up action of the nozzle. Since it remains stationary, the baffle's slightest movement causes a rapid change in output pressure. This action is identical to an on-off controller's.

To achieve automatic reset, yet preserve stability, we have to throttle valve R so air bleeds slowly into bellows Y whenever a load change occurs. Thus, the proportioning action of bellows X can be retained because any load change causing a baffle movement immediately produces a change in output pressure, and bellows X repositions the

nozzle accordingly. As air slowly bleeds into X, lever T is gradually forced to its original position preceding the load shift.

In demonstrating this action, let's adjust valve R to admit air gradually to bellows Y, Fig. 5. In practice, stability of the process governs this bleed rate; otherwise, a cyclic condition may be set up.

Imposing a 50% load we observe that the pen levels out and holds at the 50 mark. Suppose we change the load to 75%. Pen swings about 20 chart units to right of control band, stops, and as the reset action continues to function, slowly returns to the control point. Controller has thus compensated for a load change. If the load is now returned to 50% the pen swings about 20 units to left of control band, then slowly returns to original position.

While the controller now compensates for load changes, its recovery speed is too slow. Increasing the reset rate may help at times but at others a higher reset rate may give unstable control. What we need is an auxiliary device to increase recovery speed without impairing reset or proportional action.

Reviewing the action of the on-off controller we find that any slight motion transmitted to the baffle by the pen causes a rapid change of output pressure. Because of lack of follow-up action by the nozzle, a minute movement of the baffle caused an instantaneous change in nozzle backpressure. If this action can be incorporated in our proportional system, response rate of

the controller is greatly accelerated.

Slowing Follow-up Action. Evidently, nozzle follow-up cannot be entirely eliminated if proportional response is to be retained. But if nozzle movement is momentarily interrupted as the baffle assumes a new position, output from the controller momentarily changes at a rapid rate. If follow-up action could then be restored, the instrument would again perform as a proportional controller.

Recalling that follow-up is produced by air-pressure impulse delivered to bellows X, desired momentary interruption is achieved by installing a restricting needle valve P in the air lines feeding bellows X, Fig. 5.

Controller now operates thus: A slight pen disturbance causes baffle to change position in relation to nozzle, and thus generate a rapid change in output pressure. Since needle valve P restricts air flow, proportional action of bellows X is greatly retarded, and this holding back allows output pressure to increase or decrease rapidly. Such acceleration provides the increased rate of controller response we require.

The term *rate response* is generally applied to such controller action. As air continues to bleed through needle valve P, the proportioning bellows eventually causes nozzle to assume its correct position in relation to baffle and thus preserve proportional action.

Let's make use of this response by partly closing needle valve P and repeating the load change previously shown with proportional plus reset response. Load on the process is set at 50%, throttling range remains at 100%, while reset rate is increased slightly by opening needle valve R farther. These three adjustments correspond to the three adjusting knobs on a conventional instrument and are set in accordance with process stability.

Load-Change Action. If we increase the load to 75% the pen swings but four or five chart units away from the control band and quickly returns. Decreasing load to 50% shows the same action in the opposite direction. Deviation from the control band is reduced from 20 units to about five, and recovery time is reduced considerably.

While this test shows an accelerated recovery following an instantaneous load change from 50 to 75%, the majority of processes do not receive such an abrupt upset in actual practice. It is more likely that the load change will occur at a far slower rate. Rate response will assist greatly in stabilizing the control in such cases since it causes