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Evaluation of Letdown System Performance

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Abstract

A computer code to simulate the letdown system was developed to analyze the hydrodynamic transients. It was found that valve plug characteristics have a significant effect on the system stability, and that the plant specific valve control system setpoints should be determined based on the characteristics of procured valves by using a simulation code, before performing the plant startup test. The letdown system instability was evaluated for the feedback to the design of future plants.

1. Introduction

The letdown flowrate is controlled by a letdown control valve which the pressurizer level control system modulates. A backpressure control valve maintains the pressure required to prevent flashing in the letdown line. The letdown system performance is dependent on the control systems and valve trim characteristics. If the letdown system could not satisfactorily respond to simulated plant load changes, it will cause flow and pressure transients in the letdown line. The severe transients may result in excessive relief valve lifts and damage to the piping.

In this paper, the discussion is focused on the flow transients in the letdown line. A computer code based on the method of characteristics was newly developed to simulate the situation. The code models the letdown system including a letdown control valve, a letdown heat exchanger, backpressure control valve, and letdown pipeline. Incompressible flow is assumed and the heat exchanger is treated just as one of the flow resistance. The developed computer code is verified by comparing with actual test results. This code could be used to predict the performance of letdown system and the analysis results will be utilized in selecting the valve plug characteristics. The system responses to the various plug forms are compare to find the effect of plug form difference. The effect of controller setpoint is also discussed.

2. Background Information

Primary coolant is released from the reactor coolant system (RCS) at the condition of 72 gpm, 565 °F, and 2235 psig. The coolant first passes through two isolation valves, then regenerative heat exchanger, letdown control valve (LCV), letdown heat exchanger, and backpressure control valve (BCV) before being filtered and sprayed into the volume control tank (VCT). During normal operation, a selected LCV modulates the letdown flowrate between 30 and 135 gpm to maintain the pressurizer water level at programed setpoint. One of the two BCVs maintains a normal upstream pressure of 460 psig to prevent coolant from flashing in the letdown flow control valves. The letdown relief valve which has a setpoint of 600 psig is installed to protect the piping from overpressure. The YGN 3 experienced flow and pressure instabilities in the letdown line. A special test was conducted on the letdown and backpressure control system to diagnose the instability problem. With the test results, an evaluation of the letdown system design, piping arrangement, component design, control system design, and system operation was conducted. The new valve characteristics that the valve vendor proposed for the LCV and the BCV were evaluated and accepted based on results from computer modeling of the letdown line. The revised trims were selected to provide control over the entire flow region with wider operating band and longer lift. After the modifications such as changes of the control valve trim and control logic, a retest (hereafter mini-HFT) was conducted.

3. Theoretical Analysis [1,2]

The equation of motion of one dimensional flow through a constant area tube is expressed as

$$L_1 = gH_x + V_t + \frac{fV|V|}{2D} = 0 \qquad (1)$$

This is the simplified hydraulic grade line form of the equation of motion. In deriving this equation low Mach number - substantially constant density - is assumed and Darcy-Weisbach friction factor relation is used. The unsteady continuity equation is

$$L_2 = \frac{a^2 V_x}{g} + H_t = 0 \qquad (2)$$

The above two equations are transformed to four ordinary differential equations by the characteristic method.

$$C^+ : \begin{cases} \frac{g}{a}\frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 & (3) \\ \frac{dx}{dt} = a & (4) \end{cases}$$

$$C^- : \begin{cases} -\frac{g}{a}\frac{dH}{dt} + \frac{dV}{dt} + \frac{fV|V|}{2D} = 0 & (5) \\ \frac{dx}{dt} = -a & (6) \end{cases}$$

By integrating Equations (3) and (5) along suitable characteristic line and transforming into finite difference form, the two compatibility equations can be written as

$$C^{+} \; : \; H_i = C_P - B_P Q_i \tag{7}$$

$$C^{-} \; : \; H_i = C_M + B_M Q_i \tag{8}$$

in which C_P, B_P, C_M and B_M are known constants whose values are respectively

$$C_P = H_{i-1} + BQ_{i-1} \quad B_P = B + R|Q_{i-1}| \tag{9}$$

$$C_M = H_{i+1} - BQ_{i+1} \quad B_M = B + R|Q_{i+1}| \tag{10}$$

where $B = \frac{a}{gA}$ and $R = \frac{f\Delta x}{2gDA^2}$.

From Equations (9) and (10) we can calculate current values of head and flowrate if we know the values of those in the previous step.

The schematic diagram of letdown system for characteristic method is shown in Figure 1. Since we focus our interest in the piping system between two control valves, we have following two boundary conditions. Upstream boundary condition can be expressed along the C^{-} characteristics as

$$Q_{1,1} = -C_v B_M + \sqrt{(C_v B_M)^2 + 2C_v(H_{uu} - C_M)} \tag{11}$$

where $C_v = \frac{Q_o^2}{2\Delta H_o}\left(\frac{K_o}{K}\right)$.

By applying similar process to the backpressure control valve, the downstream boundary condition can be expressed as

$$Q_{4,NS} = -C_v B_P + \sqrt{(C_v B_P)^2 + 2C_v(C_P - H_{cc})} \tag{12}$$

The letdown heat exchanger comprises of two water boxes which are connected by a number of small tubes (Figure 2). The factor R in the compatibility equation, when Moody diagram friction factor is used, becomes

$$R_c = \frac{f_s \Delta x}{2gD_s A_T^2} \tag{13}$$

The wave propagation velocity must be appropriate to the smaller diameter tube and $B = a_s/gA_T$. Water box is treated as lumped capacitance of the pipe line. Therefore the continuity equation at the junction becomes

$$Q_{2,NS} = Q_{3,1} + Q_w \tag{14}$$

An effective bulk modulus of elasticity K_e, is used to describe the elastic effect of the fluid and the water box.

$$K_e = \frac{\Delta p}{\Delta V_w / V_w} \tag{15}$$

If the flow is positive into the water box, integration of continuity equation, dV/dt = inflow over two time steps in the staggered grid (which will be used to integrate compatibility equations), yields

$$\Delta V_w = (Q_{3,1}' + Q_{3,1})\Delta t \qquad (16)$$

where primed quantities refer values for the current time step and those unprimed refer the values for the two time step earlier. Equations (15) and (16), when combined, become

$$H_{3,1}' = H_{3,1} + \frac{K_e \Delta t}{\gamma V_w}(Q_{3,1} + Q_{3,1}') \qquad (17)$$

The upstream water box is handled by a combined solution of Equations (14) and (17) with compatibility equations, (7) and (8).

The letdown control system and the backpressure control system consist of proportional-integral (PI) controller. For a direct-acting controller, the descriptive equation is

$$m(t) = \overline{m} + K_c[c(t) - r(t)] + \frac{K_c}{T_I}\int[c(t) - r(t)]dt \qquad (18)$$

The valve positions are determined from Eq. (18), taking the valve stiction effects into account. Figure 3 shows the block diagram of letdown control system and backpressure control system.

4. Results

The developed code has been benchmarked by comparing the simulation results with transients data obtained during the mini-HFT performed in YGN 3. Although there are some differences in frequency and amplitude of the letdown backpressure spike, the simulation results demonstrated consistency in transients trends as shown in Figure 4. For the practical purpose, the code could be used as a design tool to predict the letdown system performance.

The effects of controller setpoints have been evaluated in this study (see Figure 5). It is deduced that the improper control setpoints might have resulted in opening of relief valve during intial HFT period and damaged the piping in setting the setpoint values by trial and error method. The setpoints of the pressurizer level control system should be in good harmony with the backpressure control system to prevent the instability of letdown system. Not only the performance of pressurizer level control system but also the stability of letdown backpressure control system should be checked before performing the plant startup test.

The modified equal percentage type of BCV has been verified to be more proper than the linear type which is the current design requirement. The equal percentage form showed stable controllability at low stroke especially (see Figure 6). The valve stiction affects the transients significantly but the valve speed is negligible within the range of stroke time (1-5 sec) in the valve specification.

5. Conclusions

Because not only the valve characteristics but also the controller setpoints affect the system stability, the performance of the letdown line should be simulated by using this computer code prior to startup test. It will avoid trial and error in determining the setpoints during startup test and avoid reoccurrence of the same problem as YGN 3.

For further work, the realistic movements of control valves should be modeled into the simulation. The behaviour of relief valve chattering also needs to be incorporated into the code to analyze the impact of water hammer in letdown pipeline. If this code is extended to include the rest of CVCS, it could be used for performance analyses of main loop of CVCS. Such refinement of simulation code is left for the future study.

Nomenclature

A	area of pipe
A_T	total flow area of heat exchanger tube side
a	wave velocity
B	pipeline characteristic impedance
Cv	valve flow coefficient
C_v	valve coefficient
C^+, C^-	name of characteristic equations
c	controlled variable
D	pipe inside diameter
f	Darcy-Weisbach friction factor
g	acceleration of gravity
H	piezometric head; hydraulic grade line elevation
H_{cc}	downstream pressure of the backpressure control valve
H_{uu}	upstream pressure
K	head loss coefficient
K_c	controller gain
K_e	effective bulk modulus of elasticity
L	length of pipeline section
m	output from controller
m	bias value
N	number of reaches in pipeline
NS	number of the last node ($=N+1$)
p	pressure
Q_i	pipeline flow at section i or node i
$Q_{i,j}$	pipeline flow at node j of section i
R	pipeline resistance coefficient
r	setpoint
s	as a subscript denotes small-diameter tubes of heat exchanger
T_I	reset time
t	time; as a subscript denotes partial differentiation
V	flow velocity
V_W	volume of water box
x	distance along pipe; as a subscript denotes partial differentiation
0	as a subscript denotes initial steady condition
γ	specific weight of fluid ($= \rho g$)
ρ	mass density

References

1. E. B. Wylie, and V. L. Streeter, and L. Suo, *Fluid Transients in Systems,* Prentice-Hall, Englewood Cliffs (1993)

2. V. L. Streeter and E. B. Wylie, *Fluid Mechanics*, McGraw-Hill Book Co., Singapore (1983)

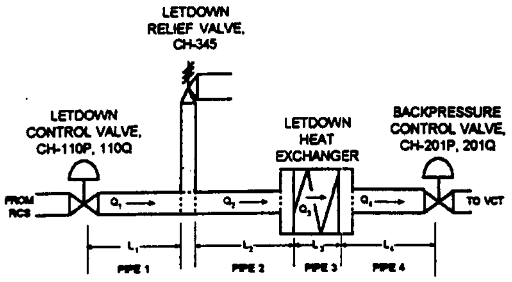

Figure 1. Schematic Diagram of Letdown Subsystem for Characteristic Method

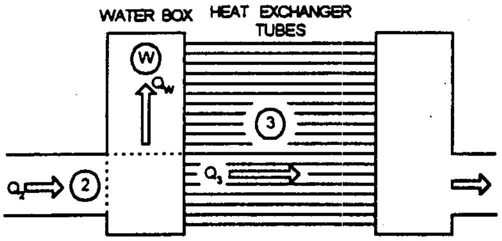

Figure 2. Schematic Diagram of Letdown Heat Exchanger

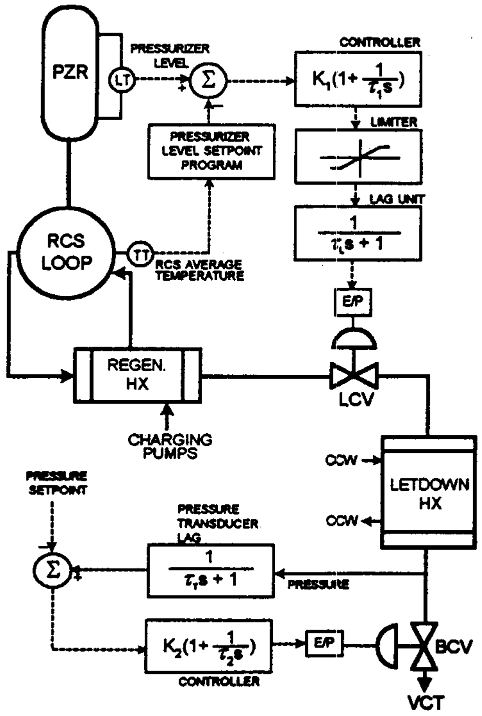

Figure 3. Block Diagram of Letdown Flow Control System and Letdown Backpressure Control System

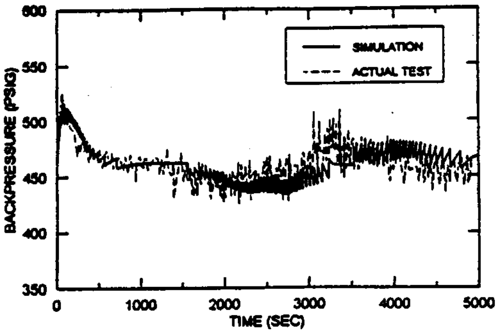

Figure 4. Comparison of Backpressure Transients between Actual Test Data and Simulation

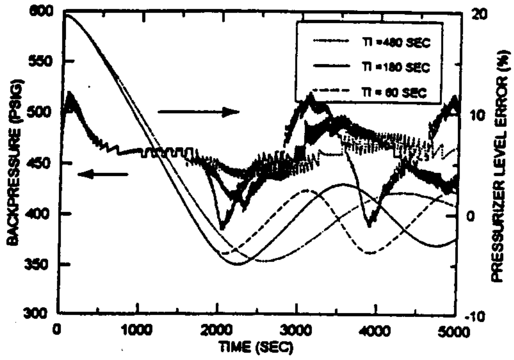

Figure 5. Effects of LCV Reset on Backpressure and Pressurizer Level

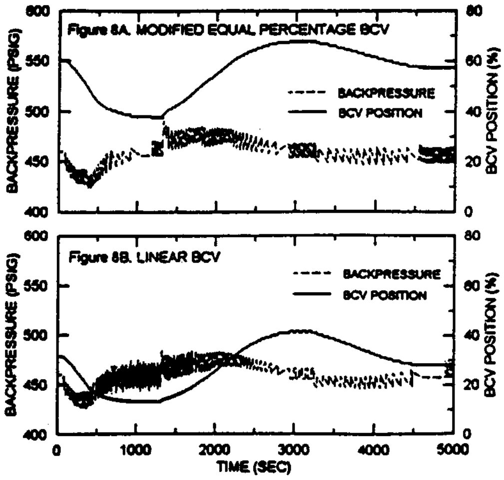

Figure 6. Comparison of Effects of linear and Equal Percentage BCV on Backpressure (with Mini-HFT Control setpoints)