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1977 POWER INDUSTRY COMPUTER APPLICATIONS CONFERENCE

PICA-77

MAY 24-27, 1977

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FOREWORD

This volume contains the complete text of the technical papers accepted for presentation at the Tenth Power Industry Computer Applications Conference in Toronto, Ontario, Canada, May 24-27, 1977.

This volume will be the only published record of the completed papers. Abstracts will appear in Power Apparatus and Systems. Written discussions and the author's closure for these papers will be published in a supplemental volume which will be distributed after the conference.

Our thanks are due to the many persons who contributed their time and talent to review these papers. The authors themselves are, of course, the people who make a technical conference possible, and their efforts to share their ideas, and the fruits of their work with us are deeply appreciated.

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NUCLEAR POWER COMPUTATIONS

A SIMULATION STUDY OF DEAERATOR CONTROL FOR CANDU NUCLEAR POWER PLANTS

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ABSTRACT

The deaerator for CANDU nuclear power plants is modelled and simulated for the purpose of investigating its dynamic behaviour under various operating conditions and designing suitable control schemes for its pressure and level control.

The mathematical model consists of two parts - equilibrium and non-equilibrium thermodynamic models, with a provision to switch from one model to the other depending on the relative thermodynamic conditions of the liquid and vapour phases. The fidelity of the model is satisfactorily verified by comparing simulation results of the Pickering Generating Station deaerator with available field data.

Digital control algorithms are developed to meet the deaerator control requirements, particularly under the 'Reactor Poison Prevent' operation. The effects of varying control parameters and sampling time are also discussed.

INTRODUCTION

In a CANDU nuclear power plant the deaerator serves the dual functions of heating boiler feedwater to a minimum permissible temperature of around 240°F and liberating corrosive, dissolved gases in the feedwater. As illustrated in Figure 1, it is made up of a heater vessel located on and draining into a large water storage tank. Heating steam is extracted from the L.P. turbine during normal operation or from the main steam line in abnormal situations and injected into the deaerator at the two ends of the heater vessel. Condensate from the L.P. heaters and the H.P. heaters drain are sprayed down from the top of the heater vessel and the mixture is heated by the incoming steam as it cascades down a stack of perforated trays. Liberated gases are vented to atmosphere and water flowing from the heater vessel is admitted to the storage tank through drain downcomers and a distribution header which inhibits thermal stratification. The deaerator storage tank receives boiler feed pump recirculation flow if the feedwater flow drops below the minimum allowable flow for one pump.

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MATHEMATICAL MODELS[1,2]

There are two possible approaches to model a deaerator: equilibrium thermodynamic model or non-equilibrium thermodynamic model. In the equilibrium model, it is assumed that the liquid and vapour phases in the deaerator are in saturation, so the equations of conservation of mass and energy are applied to the liquid and vapour as a whole. The non-equilibrium model takes into consideration the mechanism between the vapour phase and the liquid phase; the average properties of the two phases are not necessarily in thermodynamic equilibrium and the conservation equations of mass and energy are applied to each phase separately.

During the start-up or poison prevent* modes of operation, a large amount of heating steam required by the deaerator is extracted directly from the main steam line. Because this steam is at a much higher temperature and pressure than the conditions in the deaerator, it will superheat the vapour phase in the vessel. For this reason a non-equilibrium model is deemed necessary for the simulation study for deaerator control. The dynamics between the vapour phase and the liquid phase depends on the net condensation (or evaporation) rate which is a function of many factors, including the relative thermodynamic conditions between the phases, the condensate flow rate and the geometry of the vessel.

If the temperature of the liquid in the deaerator is higher than the saturation temperature corresponding to the vapour pressure, there will be net evaporation (flashing), otherwise there will be net condensation. Flashing is known to be a very fast process and it tends to maintain

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* Following a reactor shutdown or load reduction, Xenon builds up and eventually causes the reactor to "poison out". Consequently, the reactor becomes unavailable for approximately forty hours. To prevent this after a turbine trip or large turbine load reduction, the reactor may be operated at some minimum power level indefinitely without being poisoned out. For Pickering Generating Station A this level is around 70% full power. The generated steam is discharged to the atmosphere or to the main condenser.

equilibrium between the two phases. Instead of estimating the rate of flashing with heat transfer coefficients, the method here is to switch the computation to use the equilibrium model when such conditions prevail. This is deemed to be more accurate as well as computationally stable.

Non-Equilibrium Thermodynamic Model of Deaerator

The dynamic behaviour of the deaerator is obtained from the equations of conservation of mass and energy (written separately for the liquid and vapour phases), the equations of state, the boundary conditions due to geometrical constraints and assumptions regarding heat exchange at the trays and regarding the rate of condensation.

With the symbols defined in Figure 2, the equations for conservation of mass are:

$$\dot{M}_V = W_{ESTM} + W_{ESTT} - W_{CST} - W_{RFV} \quad (1)$$

$$\dot{M}_L = W_{CST} + W_{CON} + W_{HPD} - W_{FDW} \quad (2)$$

where the gas vent flow and feedwater recirculation flow have been neglected.

It is assumed that the condensate, the H.P. heaters drain and the condensed steam mix thoroughly in the trays of the heater vessel and drain into the storage tank at one mixture enthalpy h_F. This assumption is based on the design intent of the trays for thorough mixing and homogeneous heating and may be mathematically expressed as:

$$W_{CST}h_V + W_{CON}h_{CON} + W_{HPD}h_{HPD}$$

$$= (W_{CST} + W_{CON} + W_{HPD})\ h_F \quad (3)$$

The equations for conservation of energy are:

$$(M_V\dot{u}_V + \dot{M}_V u_V) = W_{ESTM}h_{ESTM} + W_{ESTT}h_{ESTT}$$

$$- W_{CST}h_V - W_{RFV}h_V - \frac{P\dot{V}_V}{J} \quad (4)$$

$$(M_L\dot{u}_L + \dot{M}_L u_L) = (W_{CST} + W_{CON} + W_{HPD})\ h_F$$

$$- W_{FDW}h_L + Q_H - \frac{P\dot{V}_L}{J} \quad (5)$$

Relating enthalpy to internal energy and total volume to specific volume gives:

$$h_V = u_V + \frac{Pv_V}{J} \quad (6)$$

$$h_L = u_L + \frac{Pv_L}{J} \quad (7)$$

$$V_V = M_V v_V \quad (8)$$

$$V_L = M_L v_L \quad (9)$$

The geometrical constraint is a constant deaerator volume:

$$V_V + V_L = V \quad (10)$$

Because the vapour in the deaerator is likely to be superheated, the pressure is expressed as a function of two other vapour properties:

$$P = P(h_V,\ v_V) \quad (11)$$

where the functional relationship is obtained from the superheated steam tables. On the other hand, water may be considered incompressible and therefore its specific volume may be expressed as:

$$v_L = v_{LSAT}(h_L) \quad (12)$$

where the functional relationship is obtained from the saturation steam tables.

Equations (1) to (12) contain the basic thirteen unknowns: M_V, M_L, u_V, u_L, h_V, h_L, h_F, W_{CST}, v_V, v_L, V_V, V_L, P. All other variables may be either directly computed from these unknowns or are determined by factors external to the deaerator, in which case they are considered as inputs to the simulation. It remains to estimate W_{CST}, the rate of condensation of steam due to the heat exchange at the trays.

At any given pressure, the maximum rate of condensation of steam is that which will raise the enthalpy of the liquid mixture ($W_{CST}+W_{CON}+W_{HPD}$) to the saturation liquid enthalpy corresponding to that pressure ($h_{FSAT}(P)$). This maximum condensation rate may be obtained from equation (3) as:

$$W^*_{CST}h_V + W_{CON}h_{CON} + W_{HPD}h_{HPD}$$

$$= (W^*_{CST} + W_{CON} + W_{HPD})\ h_{FSAT}(P) \quad (13)$$

$W_{CST}{}^*$ is considered as a driving force and the actual rate of condensation is assumed to be a first order lag to it:

$$\dot{W}_{CST} = \frac{1}{\tau_{CST}} (W^*_{CST} - W_{CST}) \quad (14)$$

Two implications of the last equation may be noted. Firstly, the time constant τ_{CST} is a measure of how fast the condensation rate approaches the maximum condensation rate during a transient. Secondly, the steady state rate of condensation is the maximum rate corresponding to the steady state pressure. The enthalpy of the liquid mixture draining into the storage tank will then be $h_{FSAT}(P)$ and the vapour and liquid phases in the deaerator will be in saturation. This is consistent with the heat balance data of Pickering and Bruce Generating Stations which indicate that during steady state normal operation, the vapour and liquid phases in the deaerator are in saturation and the enthalpy of the liquid draining from the heater vessel to the storage tank is saturated with respect to the pressure. τ_{CST} is therefore also a measure of how fast the two phases return to equilibrium after a disturbance. The value chosen for τ_{CST} will be based on field data.

The immersion heaters are controlled solely by the temperature of the water in the storage tank:

$$Q_H = f(T_L) \quad (15)$$

The temperature of the water is considered independent of the pressure and may be determined from its enthalpy:

$$T_L = T_{LSAT}(h_L) \quad (16)$$

where the functional relationship is obtained from the saturation steam tables.

Flow through the relief valve depends on the deaerator pressure and is expressed as:

$$W_{RFV} = \begin{cases} 0 & \text{if } P < P_0 \\ K_{RFV} \dfrac{P-P_0}{P_{100}-P_0} & \text{if } P_0 \leq P \leq P_{100} \\ K_{RFV} & \text{if } P > P_{100} \end{cases} \quad (17)$$

where, P_0 = pressure at which relief valve start to open

P_{100} = pressure at which relief valve is fully open

K_{RFV} = capacity flow of relief valve

In each iteration the water level is incremented by the increment in water volume divided by the water surface area:

$$\Delta \ell = \frac{\Delta V_L}{AREA} \quad (18)$$

The water surface area is a function of the water level and the deaerator geometry and is updated in every iteration. With reference to Figure 3, it is given by:

$$AREA = \begin{cases} 2L_1\sqrt{2R_1\ell-\ell^2} \\ \quad \text{if } 0 \leq \ell < 2R_1 \\ C \text{ if } 2R_1 \leq \ell \leq (2R_1+H) \\ 2L_2\sqrt{2R_2\hat{\ell}-\hat{\ell}^2} \\ \quad \text{if } (2R_1+H) < \ell \leq (2R_1+H+2R_2) \end{cases} \quad (19)$$

where, C = cross sectional area of pressure equalizer plus water downcomers

$\hat{\ell} = \ell - 2R_1 - H$

The feedwater flow, H.P. heaters drain flow and L.P. turbine extraction steam flow are all dependent on conditions external to the deaerator and are therefore inputs to the simulation. For the poison prevent operation of a typical CANDU nuclear power plant, the boiler feedwater demand drops to 70% of the full power demand while the H.P. heaters drain and L.P. turbine extraction are cut off by non-return valves.

The condensate flow and steam flow from the main steam line are determined by the level and pressure control schemes respectively.

Equilibrium Thermodynamic Model of Deaerator

When the deaerator pressure drops below the saturation pressure corresponding to the water temperature, flashing ensues and equilibrium is maintained between the two phases. When such conditions occur, the computation is switched to the equilibrium model.

A significant simplification in the equilibrium model is possible by taking advantage of the fact that the mass of liquid is much greater than the mass of vapour in the deaerator. In order to maintain equilibrium between the two phases, practically all the incoming steam has to condense.

The equations of conservation of mass and energy are written for the vapour-liquid combination as a whole:

$$\dot{M}_L + \dot{M}_V \doteq \dot{M}_L = W_{ESTM} + W_{ESTT} + W_{CON} + W_{HPD} - W_{FDW} - W_{RFV} \quad (20)$$

$$(\dot{M_L u_L}) + (\dot{M_V u_V}) \doteq (\dot{M_L u_L})$$

$$= W_{ESTM}h_{ESTM} + W_{ESTT}h_{ESTT} + W_{CON}h_{CON}$$

$$+ W_{HPD}h_{HPD} - W_{FDW}h_L - W_{RFV}h_V + Q_H \quad (21)$$

Equations (20) and (21) may be solved for M_L and u_L from which all other variables may be determined for saturation conditions.

Heat from the immersion heaters, relief valve flow, water level, feedwater flow, H.P. heaters drain flow and L.P. turbine extraction steam flow are determined in a similar fashion as in the non-equilibrium model.

Pressure Control

During the start-up or poison prevent modes of operation of a CANDU nuclear power plant, deaerator pressure is controlled by regulating the amount of heating steam extracted from the main steam line. Difficulty in pressure control has been experienced at the Pickering Generating Station with the use of an analog PI controller. Simulation results also indicate poor pressure control with the use of a PI algorithm but significant improvement is achieved with the use of a properly tuned PID algorithm (analog or digital), and/or with the use of a faster stroking pressure control valve.

The analog PID algorithm for pressure control may be expressed as:

$$Y_P = K_{CP}\left[1 + \frac{1}{\tau_{IP}s} + \frac{\tau_{DP}s}{\frac{\tau_{DP}}{G}s+1}\right]E_P \quad (22)$$

where, E_P = $P_{SET} - P$

P_{SET} = pressure set point

Y_P = normalized control signal to pressure control valve

K_{CP} = normalized gain

τ_{IP} = reset time

τ_{DP} = rate time

G = derivative filter factor

s = Laplace variable

The equivalent digital PID alogrithm may be expressed either in the position or velocity form.[4,5]

Position Algorithm:

$$Y_P(N) = K_{CP}\left[E_P(N) + D_P(N)\right] + I_P(N) \quad (23a)$$

$$D_P(N) = \frac{\tau_{DP}}{T_{SP}}\left[1 - \varepsilon^{\frac{-T_{SP}G}{\tau_{DP}}}\right]\left[E_P(N) - E_P(N-1)\right] + \varepsilon^{\frac{-T_{SP}G}{\tau_{DP}}} D_P(N-1) \quad (23b)$$

$$I_P(N) = I_P(N-1) + \frac{K_{CP}T_{SP}}{\tau_{IP}}E_P(N) \quad (23c)$$

where, N = N^{th} sampling instant

T_{SP} = sampling time for pressure control

Velocity Algorithm:

$$Y_P(N) = Y_P(N-1) + \Delta Y_P(N) \quad (24a)$$

$$\Delta Y_P(N) = K_{CP}\left[E_P(N) - E_P(N-1)\right] + K_{CP}\,\Delta D_P(N) + \frac{K_{CP}T_{SP}}{\tau_{IP}}E_P(N) \quad (24b)$$

$$\Delta D_P(N) = \frac{\tau_{DP}}{T_{SP}}\left[1 - \varepsilon^{\frac{-T_{SP}G}{\tau_{DP}}}\right] \times \left[E_P(N) - 2E_P(N-1) + E_P(N-2)\right] + \varepsilon^{\frac{-T_{SP}G}{\tau_{DP}}}\Delta D_P(N-1) \quad (24c)$$

With the position algorithm, the computer calculates the desired position of the manipulated variable after every sampling instant -- in this case, the opening of the control valve. With the velocity algorithm, the desired change in position is calculated.

Second order valve characteristics are assumed in computing the response of the pressure control valve to the control signal:

$$S_P = \frac{Y_P}{1 + \frac{2\zeta_P}{\omega_{NP}} s + \frac{1}{\omega_{NP}^2} s^2} \qquad (25)$$

where, S_P = lift of pressure control valve
ζ_P = damping factor of pressure control valve
ω_{NP} = natural frequency of pressure control valve

The steam flow rate through the valve is expressed as:

$$W_{ESTM} = \rho_{ESTM} K_P S_P \sqrt{P_{ESTM} - P} \qquad (26)$$

where, ρ_{ESTM} = density of steam at the control valve
K_P = pressure control valve constant
P_{ESTM} = pressure upstream of pressure control valve

Level Control

Deaerator level control is achieved by modulating the condensate flow into the deaerator. Due to the large size of the deaerator storage tank, level fluctuations are slow. This is ideal for digital control because the requirements on the rate of sampling is fairly relaxed.

A three-element PI algorithm for level control may be expressed as:

$$Y_L = K_{CL1}\left[1 + \frac{1}{\tau_{IL1} s}\right] E_L + K_{CL2}\left[1 + \frac{1}{\tau_{IL2} s}\right] E_F \qquad (27)$$

where, E_L = $\ell_{SET} - \ell$
E_F = $W_{FDW} - W_{CON}$
ℓ_{SET} = level set point
Y_L = normalized control signal to level control valve

and other symbols are defined as in equation (22).

The equivalent digital algorithms are:

Position Algorithm:

$$Y_L = K_{CL1} E_L(N) + K_{CL2} E_F(N) + I_L(N) \qquad (28a)$$

$$I_L(N) = I_L(N-1) + \frac{K_{CL1} T_{SL}}{\tau_{IL1}} E_L(N) + \frac{K_{CL2} T_{SL}}{\tau_{IL2}} E_F(N) \qquad (28b)$$

where T_{SL} is the sampling time for level control.

Velocity Algorithm:

$$Y_L(N) = Y_L(N-1) + \Delta Y_L(N) \qquad (29a)$$

$$\Delta Y_L(N) = K_{CL1}\left[E_L(N) - E_L(N-1)\right] + K_{CL2}\left[E_F(N) - E_F(N-1)\right] + K_{CL1}\frac{T_{SL}}{\tau_{IL1}} E_L(N) + K_{CL2}\frac{T_{SL}}{\tau_{IL2}} E_F(N) \qquad (29b)$$

The response of the level control valve and the condensate flow rate are determined by equations similar to equations (25) and (26).

At Bruce and future Generating Stations, deaerator level control valves are protected from cavitation by being located upstream of the L.P. heaters. Taking into account the dynamics along the piping from the level control valves to the deaerator:

$$\frac{dw_{CON}}{dt} = \frac{1}{PIPE_I}\left[P_{UP} - \left(\frac{W_{CON}}{\rho_{CON} K_L S_L}\right)^2 - P - P_{HEAD} - PIPE_R W_{CON}\right] \qquad (30)$$

where, ρ_{CON} = density of condensate at the control valve
K_L = level control valve constant
S_L = lift of level control valve