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Study on the Discharge Transients of Blowdown Flows in a Pipe

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Abstract

The blowdown transient pipe flows resulting from the actuation of the safety/relief valve (SRV) under valve opening conditions have been analyzed. The analytical model has been developed for a uniform pipe with friction through which the flow is discharged into a suppression pool in case of a sudden opening of the SRV. The piping flow characteristics and dynamic loads are calculated. Effects of system pressure, pipe length and submergence depth are included.

1. Introduction

All boiling water reactor (BWR) plants are equipped with a number of safety/relief valves(SRVs) to control large primary system pressure transients. The SRVs are mounted on the main steam lines inside the drywell; discharge lines are routed through the drywell into the suppression pool. When an SRV is actuated, the steam released from the primary system is discharged into the suppression pool and condensed. Upon the actuation of SRV, the air column within the partially submerged discharge line is compressed by the high pressure steam and , in turn, accelerates the water leg into the suppression pool. Thus, the water jets formed create pressure and velocity transients which are manifested as drag or jet impingement loads on submerged structure.

Steam discharge tests conducted by ABB-Atom have clearly shown that there are parameters which have any significant influence on the gas cloud pressure amplitude for a given sparger design. Experiment and operating experience have shown that the magnitude of the SRV discharge related loads is a strong function of the geometry and configuration of the discharge device utilized.

The steam discharge system releases steam from the pressurizer of RCS and depressurizes RCS in a PWR. KNGR design which is currently under development has the design concept of a steam discharge system with IRWST and it is quite clear that the technology to support the design of our KNGR needs to be urgently secured.

Even though the physics is all the same between BWR and PWR in the steam release system, there are some basic differences between BWR and PWR. They are system operation pressure, temperature, the number of valves for each discharge line and valve characteristics. Because of this basic differences there should be a high level of generality in methodology when methodolgy developed for BWR is to be used successfully for PWR design development.

The analysis of SRV discharge transients is required to determine the piping dynamic loads to be used to for structural design of the piping and its supports. The pressure and the velocity of the air/water interface at the end of water slug clearing are important quantities for piping design purposes.

A numerical solution of the equations that govern unsteady fluid flow in pipelines has been developed. A general solution to the partial differential equations is not available; however, the partial differential equations may be transformed by the method of characteridtics into particular total differential equations. The latter equations may then be integrated to yield finite difference equations, which are conveniently handled numerically.

It is the purpose of this study to analyze the piping flow characteristics and determine the piping dynamic loads in pipe design, which includes effects of system pressure, pipe length and submergence depth for sudden discharge.

2. Mathematical Analysis

The one dimensional basic equations of mass, momentum and energy conservation for a non-heat conducting fluid in a uniform pipe with friction are given by,

Mass conservation

$$\frac{\partial \rho}{\partial t} + V\frac{\partial \rho}{\partial x} + \rho\frac{\partial V}{\partial x} = 0 \tag{1}$$

Momentum conservation

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} = -\frac{1}{\rho}\frac{\partial p}{\partial x} - \frac{f}{D}\frac{V|V|}{2} \tag{2}$$

Energy conservation

$$\frac{\partial h}{\partial t} + V\frac{\partial h}{\partial x} = \frac{1}{\rho}\left(\frac{\partial p}{\partial t} + V\frac{\partial p}{\partial x}\right) + \frac{1}{2}\frac{f}{D}V^2|V| \tag{3}$$

The air initially in the pipe and the incoming steam are dealt with as ideal gases for which the enthalpy h and the sonic speed a are related by

$$h = \frac{k}{k-1}\frac{p}{\rho} = \frac{a^2}{k-1}, \qquad a^2 = k\frac{p}{\rho} \tag{4}$$

where k is the ratio of specific heats for the gas.

Fig. 1 shows a schematization of SRV piping, two flows can be identified; gas flow, and water flow. The governing equations form hyperbolic partial differential equations in terms of dependent variables such as velocity, pressure and density and independent variables such as distance along the pipe, time. The equations are transformed into ordinary differential equations by method of characteristics.

For gas flow, using eqns.(2) and (3) yields the following relations,

along the characteristic curve C^+,

$$\frac{dx}{dt} = V + a \tag{5}$$

$$dP + \frac{\rho a}{g_c}dV = \frac{f}{D}\frac{\rho}{2g_c}V|V|\{(k-1)V - a\}dt \tag{6}$$

and along the characteristic curve C^-,

$$\frac{dx}{dt} = V - a \tag{7}$$

$$dP - \frac{\rho a}{g_c}dV = \frac{f}{D}\frac{\rho}{2g_c}V|V|\{(k-1)V + a\}dt \tag{8}$$

The density can be integrated on the curve

$$\frac{dx}{dt} = V \tag{9}$$

$$d\rho - \frac{g_c}{a^2}dP = -\frac{1}{2}\frac{f}{D}(k-1)\frac{\rho}{a^2}V^2|V|dt \tag{10}$$

For water flow,

along the characteristic curve C^+,

$$\frac{dx}{dt} = V + a \tag{11}$$

$$dP + \frac{\rho a}{g_c} dV = -\frac{f}{D}\frac{\rho}{2g_c} V|V| a dt \qquad (12)$$

and along the characteristic curve C^-,

$$\frac{dx}{dt} = V - a \qquad (13)$$

$$dP - \frac{\rho a}{g_c} dV = \frac{f}{D}\frac{\rho}{2g_c} V|V| a dt \qquad (14)$$

3. Numerical Analysis and Initial, Boundary Conditions

A numerical solution using finite difference approximations is adopted to solve Eqns.(1) through (14) to determine the different flow variables as function of x and t starting from the initial conditions and satisfying the boundary conditions. A pipeline is divided into a number of reaches, N, each Δx in length as shown in Fig. 2. A constant time increment grid is chosen. In the method of specified time intervals, an interpolation procedure is necessary to find the value of points R and S. The grid is used for the gas flows as well as for the water flows. The finite difference approximations of Eqns.(6),(8) and (10) is given in the following forms;

$$P_P - P_R + \frac{\rho_R a_R}{g_C}(V_P - V_R) = \frac{f_R}{D}\frac{\rho_R}{2g_C} V_R|V_R| \cdot [(k-1)V_R - a_R] \cdot \Delta t \qquad (15)$$

$$P_P - P_S - \frac{\rho_S a_S}{g_C}(V_P - V_S) = \frac{f_S}{D}\frac{\rho_S}{2g_C} V_S|V_S| \cdot [(k-1)V_S + a_S] \cdot \Delta t \qquad (16)$$

$$\rho_P - \rho_Q - \frac{g_C}{a_Q^2}(P_P - P_Q) = -\frac{1}{2}\frac{f_Q}{D}(k-1)\frac{\rho_Q}{a_Q^2} V_Q^2 |V_Q| \cdot \Delta t \qquad (17)$$

At time t=0, the flow velocity in the pipe is zero. As the valve opens, the steam flow is given by

$$\dot{m} = A\rho_e V_e \qquad (18)$$

The flow rate at the valve is determined depending on the pressure ratio, P_e / P_o. If this pressure ratio is less or equal to the critical ratio, the flow is choked at the valve throat. If the pressure ratio is greater than the critical ratio, the valve flow is subsonic. The mass flow rate and the energy conservation at the valve provide the valve boundary conditions.

It is assumed that steam penetration into the air is negligible. The pressure and the velocity of the steam and air on each side of this interface is the same. As the air in the pipe is compressed , the water expulsion of the discharge pipe starts. On the air/water interface, the pressure and velocity on both sides are the same.

For an exit flow resistance ζ , the exit flow is controlled by,

$$P_U - P_D = \zeta \rho \frac{V^2}{2g_C} \qquad (19)$$

4. Results and Discussion

The following data are used for numerical prediction of discharge transients for PWR and BWR.

	PWR	BWR
reactor pressure, Nm^{-2}	1.72×10^7	7.93×10^6
pipe length, m	48.7	36.6
pipe submerged depth, m	3.5 - 7	3.5 -7

When the valve opens, the pressure of the air rises and its velocity increases. These changes propagate in the pipe. When the wave reaches the water surface, the air velocity decreases and a pressure wave propagates to the valve, at the same instant, the water starts moving.

The pressure and the velocity of the air/water interface at the end of water clearing are important quantites for piping design purposes. Figs. 3 and 4 show the plot of the pressure, velocity and water clearing time versus initial water submergence depth in BWR and PWR. It is found that the pressure, clearing time and clearing velocity depend on the pipe length as well as the system pressure. Although the system pressure in PWR is higher than in BWR, the pressure in the discharge piping is not significantly different due to pipe length difference.

References

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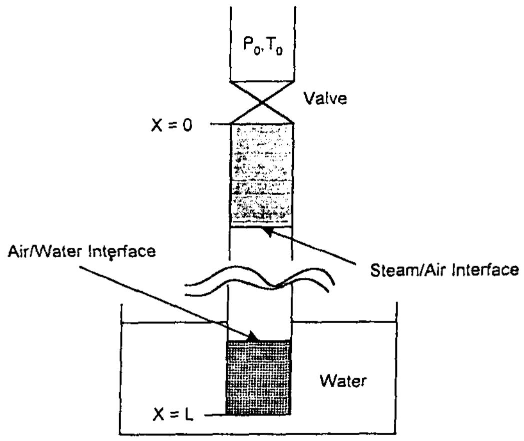

Fig. 1 Discharge Piping Model

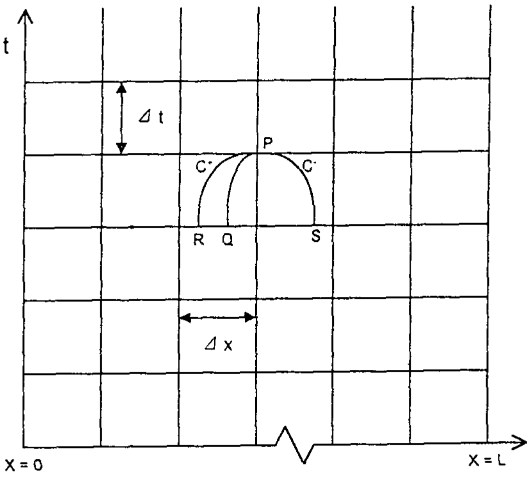

Fig. 2 Chararcteristic Lines in the X-t Plane

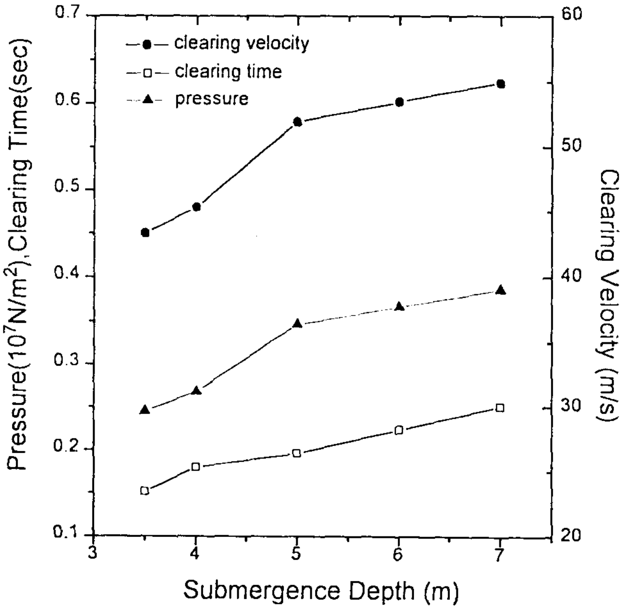

Fig. 3 Dependence of air/water interface conditions on submergence in BWR

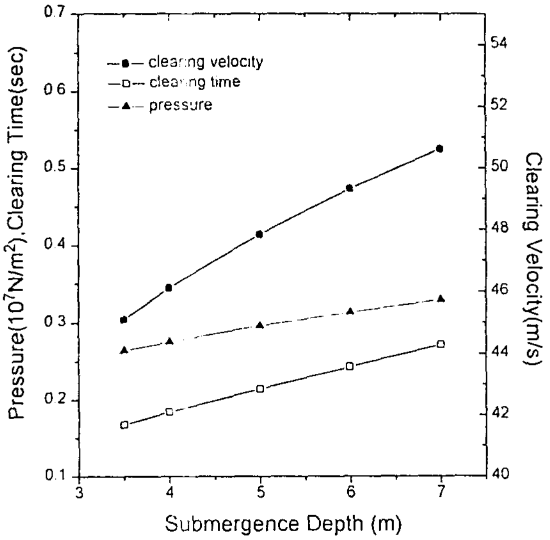

Fig. 4 Dependence of air/water interface conditions on submergence in PWR