Water Hammer in the Circulating Pipe Line with Pressure Vessels*

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Studies have been made to compare and discuss the analytical solutions obtained by the method of characteristics with the experimental results on the water hammer.

The measurements have been carried out using a 1/6 scale model of the primary coolant system of the experimental fast breeder reactor "JOYO" belonging to the Power Reactor and Nuclear Fuel Development Corporation. The water hammer has been taken place at flow velocities 0.5 and 1.0 m/s, caused by closing slowly the flow control clap valve in the time ranges 4.5~9.6 seconds and 4.6~11.2 seconds respectively.

Qualitative agreement was found between the analytical and experimental results. And the calculation gave the safety value at the peak pressure.

Therefore the calculation models and idea used in this paper have sufficient practical value.

Key Words : Unsteady Flow, Circulating Pipe Flow, Water Hammer, Nuclear Engineering, Primary Coolant System

1. Introduction

Waterhammer is one of important phenomena in fluid engineering. For example, in a reactor steam generator waterhammer is caused by rapid steam condensation in the feedwater inlet to the generator⁽¹⁾. And the phenomenon may be introduced in a primary coolant system by stopping the back flow associated with closing a check valve in the case of an accident in the system⁽²⁾.

The present paper describes an analysis by the method of characteristics to determine a pressure variation of the waterhammer when a flow control valve is closed slowly in a circulating pipeline. And we discuss the application of the method to the phenomenon with an observation.

The measurement was carried out using the model of the primary coolant system of the experimental fast breeder reactor "JOYO" belonging to the Power Reactor and Nuclear Fuel Development Corporation.

A practical importance of waterhammer has been discussed many reports^{(3)~(8)}. But there are few studies on the phenomenon in a circulating pipeline by the method of characteristics^{(9)~(11)}.

The present method has an advantage

of being applicable to not only a primary coolant loop but also a general closed pipeline.

2. Nomenclature

Ac	: opening area of clap valve
a	: speed of pressure wave
b ₁ ~b ₃	: factors to describe pump characteristic curve
Cc	: discharge coefficient of clap valve
c	: parameter of pipe constraint condition
D	: pipe diameter
E	: modulus of elasticity
e	: thickness of pipe wall
f	: Darcy-Weisbach friction factor
g	: gravitational acceleration
H	: instantaneous piezometric head
H _{p0}	: pump head of steady state
ΔH	: head loss of steady state
K	: bulk modulus of elasticity
L ₁ ~L ₄	: lengths of the first to fourth divided pipe sections
P	: instantaneous pressure
p,q,r,s	: end points of L ₁ to L ₄
T	: time of valve closure
t	: time ; time required since valve closing is started
Δt	: specified time interval
V	: instantaneous velocity
x	: coordinate along pipe centerline
Δx	: specified grid mesh interval
Z	: elevation of pipe above datum
ζ	: loss coefficient of steady state
Θ	: angular displacement of valve from full opening to closing
θ	: angular position of valve from full opening
ρ	: fluid density
τ	: ratio of effective valve opening to full opening = (CcAc)/(CcAc) _f
φ	: pipe slope

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Subscripts

G	: sluice valve
H	: pressure vessel H
R	: pressure vessel R
f	: full opening of clap valve
i	: section number along a pipe (1~4)
j	: divided section number of a pipe section
k	: time point of x-t plane
0	: steady state

3. Solution of Waterhammer Equations

3.1 Basic equations

The waterhammer equations derived by many writers⁽⁵⁾ are

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial x} = -g \left(\frac{\partial H}{\partial x} + \frac{fV|V|}{2gD} \right) \quad (1)$$

$$\frac{\partial H}{\partial t} + V \left(\frac{\partial H}{\partial x} - \sin \phi \right) = -\frac{a^2}{g} \frac{\partial V}{\partial x} \quad (2)$$

$$H = (P/\rho g) + Z \quad (3)$$

$$a = \sqrt{\frac{K}{\rho} / \left(1 + c \frac{KD}{eE} \right)} \quad (4)$$

Equations (1) and (2) form a pair of quasi-linear hyperbolic partial differential equations involving two unknowns: V and H. These expressions are transformed into two total differential equations on the characteristics $C^\pm$: $dx/dt = V \pm a$

$$dH = -\frac{a}{g} dV + \left(V \sin \phi - \frac{a}{g} \frac{fV|V|}{2D} \right) dt \quad (5)$$

$$dH = \frac{a}{g} dV + \left(V \sin \phi + \frac{a}{g} \frac{fV|V|}{2D} \right) dt \quad (6)$$

respectively.

Numerical solutions are based on the above two equations.

3.2 Assumptions of analysis

A pipeline is divided into equal reaches, each Δx in length as shown in Fig. 1. A time-step size is computed, $\Delta t = \Delta x/a$.

The calculation of the pressure and velocity in waterhammer is carried out on the basis of the following assumptions:

(1) The circulating pipeline is treated as a horizontal single pipe, since the head loss across an elbow and the head of piping are small enough to be ignored.

(2) The characteristics $C^\pm$ reduce to $dx/dt = \pm a$, since the measurements are performed under the condition: $a \gg V$.

(3) Those conditions in unsteady state are equal to the pump and valve characteristic, and the loss coefficient of pressure vessels in steady flow.

3.3 Boundary conditions

3.3.1 Clap valve

From the equation of continuity and the relationship formula of a valve are derived the boundary conditions

$$V_{k,s}^* = V_{k,1}^* \quad (7)$$

$$V_{k,s}^* = r V_0 \sqrt{\frac{H_{k,s}^* - H_{k,1}^*}{\Delta H_0}} \quad (8)$$

where V_0 is the average velocity in the pipe and ΔH_0 the head loss across the valve in steady state.

3.3.2 Pressure vessel H

Boundary conditions are obtained under the following assumptions.

(1) The vessel wall is a rigid body and the internal fluid of the vessel is incompressible, hence the elastic theory is applicable to the fluid.

(2) The vessel inlet can be connected in series with the exit, for the pressure wave appears to pass through the vessel in much less time than a calculated time-interval Δt .

Thus, we can express the equation in the form

$$V_{k,p}^* = V_{k,1}^* \quad (9)$$

$$H_{k,p}^* = H_{k,1}^* + \frac{\zeta_H}{2g} (V_{k,1}^*)^2 \quad (10)$$

in which ζ_H is a head loss coefficient across the vessel.

Fig.1 Calculating model

3.3.3 Circulating pump

The equations to represent the conditions are written as

$$V_{2,q}^2 = V_{3,1}^2 \dots\dots\dots(11)$$

$$H_{2,q}^2 + b_1(V_{2,q}^2) + b_2(V_{2,q}^2) + b_3 = H_{3,1}^2 + \frac{\zeta_g}{2g}(V_{3,1}^2) \dots\dots\dots(12)$$

where ζ_g is a head loss coefficient across the sluice valve fitted immediately behind the pump outlet.

3.3.4 Pressure vessel R

We can obtain the following relations on the basis of the same assumptions as the vessel H taking ζ_R as a head loss factor across the vessel R.

$$V_{3,r}^2 = V_{4,1}^2 \dots\dots\dots(13)$$

$$H_{3,r}^2 = H_{4,1}^2 + \frac{\zeta_R}{2g}(V_{4,1}^2) \dots\dots\dots(14)$$

4. Experimental Apparatus and Measurement

Figure 2 shows a schematic of the experimental apparatus-i.e. a scaled down model of a primary coolant system.

An unplasticized polyvinyl chloride pipe used is of 50.8 mm diameter and of 2.6 mm thickness. Pipe sections from L_1 to L_4 each correspond to those of the analytical model shown in Fig.1. Darcy-Weisbach friction factor f of the pipe was determined by measuring the head $\Delta h = f(V_0^2/2g)(l/D)$ of distance l between two measuring points and the average velocity

V_0 using a strain-gauge pressure transducer and an electromagnetic flowmeter in steady state.

The vessels R and H are associated with the reactor and the heat exchanger respectively, and are about 1/6-scale models of those of the experimental fast breeder reactor "JOYO" belonging to the Power Reactor and Nuclear Fuel Development Corporation.

The vessel R was 1260 mm in length, 500 mm in diameter, 6 mm in wall thickness and is 0.49 MPa in resisting pressure. Parallel with the vessel axis were arranged 100 copper tubes of 600 mm length, 3.8 mm diameter and 0.6 mm thickness, which corresponded to a fuel assembly in the reactor core. And 50 of these tubes were closed at both ends to obtain an appointed head loss occurring in the coolant flow through the assemblies for the complex construction of the assembly.

The vessel H was of the same construction as the vessel R, being 735 mm long and 255 mm in diameter. Seventy tubes of the same diameter and thickness were set as in the vessel R and 20 of them were closed at both ends to cause a required pressure drop.

The loss coefficients ζ_R and ζ_H of the vessels R and H respectively were determined by observing the head loss $\Delta H_R = \zeta_R(V_0^2/2g)$ and $\Delta H_H = \zeta_H(V_0^2/2g)$, and V_0 with the pressure transducer and the flowmeter in stationary state.

A circulation pump used was a volute pump whose caliber was 50 mm, specific speed 90 (m, m³/min, rpm), and rated speed 1700 rpm. A quadratic expression of V_0 was used to indicate the pumping head H_{p0} at nominal speed.

Fig.2 Schematic diagram of apparatus

The pipeline was filled with water from a reservoir by a pour water pump and was degassed, then a closed circuit was formed. The circulating pipeline was applied a pressure to 0.275 MPa with a pressurizer for the purpose of preventing cavitation and in view of the fact that most of primary coolant systems are pressurized.

Water used as a coolant was circulated by the volute pump in the direction of the arrow in Fig.2. A specified V_0 : 0.5 and 1.0 m/s was obtained by controlling a discharge valve of the pump. Under this condition the pressure variation due to the waterhammer generated by closing the clap valve slowly with a hydraulic control unit

in the range of 4.5 to 9.6 and 4.6 to 11.2 seconds respectively, was determined with a pressure transducer and recorded on an electromagnetic oscillograph through a DC amplifier.

An angular displacement θ of the clap valve and a valve closure time T were recorded on the oscillograph as variation of the current in a slide rheostat fitted to the piston of the hydraulic control unit. The one-to-one correspondence was recognized between θ/θ_0 and t/T where t was the time at θ . A clap valve throat-area ratio τ was determined in advance by the valve characteristic curve θ/θ_0 expressed as a function of t/T in steady flow.

Fig.3 Pressure variation($V_0 = 0.5$ m/s)

5. Results and Discussion

The theoretical and experimental pressure waves are shown in Figs.3 and 4 for comparison, where the numbers ① to ⑨ and H_0 denote the measuring points and an initial head of each point.

The pressure waves began to vary in the form at about $t/T = 0.5$, and the amplitude increased toward the clap valve although it decreased away from the valve. The pressure dropped from ① to ⑤ and rose from ⑥ to ⑨. The waves changed the state between the points ⑤ and ⑥ for the effect of the sandwiched sluice valve. Both pressures at the points ⑤ and ⑥ are presumed to approach an identical value with the time elapsed t/T .

It was at the valve closing time $t/T=1.0$ that the maximum pressure drop from ① to ⑤ and the maximum pressure rise from ⑥ to ⑨ took place at each point. The maximum and minimum pressures near the clap valve increased with a rise in the initial velocity V_0 for the effect of flow inertia. The maximum pressure decrement and increment were larger and the period of the waterhammer appeared to be longer in short valve closing time T than in long time. The period was obtained by a speed of pressure wave and a geometrical factor of the pipe in the experimental range, so that it seemed to be longer apparently in the case of less closure time than in long time since the pressure waves were observed by non-dimensional time t/T in the figures.

Fig.4 Pressure variation ($V_0 = 1.0$ m/s)

The theoretical results agreed qualitatively but not always quantitatively with those of observed: the analytical solutions indicated higher values than the experimental results.

It is ascribed to application of the rigid body theory to the pressure vessels H and R that there is a discrepancy between the theoretical and experimental results in the maximum and minimum pressures at the points ②, ③, ⑦, and ⑧ across the vessels. Pressure-wave propagation times through the vessels H and R were 0.42 and 0.73 millisecond respectively, and were not short enough comparing with the calculating time interval $\Delta t = 2.6$ milliseconds. For this reason there might be a compressible flow in the vessels.

The pressure wave appears to propagate three-dimensionally in the vessels of three-dimensional construction, so that the one-dimensional analytical model employed is not likely to represent exactly the practical propagation.

The characteristic quantities used in the calculation such as the loss coefficients of the valves and vessels, pipe friction factor, and pumping head curve were those of steady state corresponding to the measurement, though the flow was unsteady. We consider that the discrepancy in these quantities between the analysis and observation also affects the disagreement between the two results.

If a cavitation takes place in the pipeline, it reduces markedly the speed of pressure wave and the assumption that the wave velocity is constant can not apply to the theory and consequently the method used in the present study is not applicable to the analysis. No cavitation seemed to be generated judging from the measured pressure in the vessels and the pump and no noise generation in the pump throughout the experiment.

6. Conclusions

The theoretical results of the water-hammer pressure have agreed qualitatively with those of experimental, but the former have been large compared with the latter. The calculated values have offered the conservative result at the peak pressure. For this reason, the analytical method used in the present paper is found practically useful.

The pressure increment in the upstream side of the flow-control valve and decrement in the downstream side of the valve have increased with an approach to the valve, with a shortening of the valve closure time, and with a rise of the initial velocity in the pipe. It has been observed that the maximums of the increment and decrement take place just across the valve.

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