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Evaluation of Core Flow Rate Coastdown for Ulchin Nuclear Power Plant Unit 4

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Abstract

In the safety analysis of KSNP, the coastdown phenomena is simulated using the COAST code. The reactor coolant pump(RCP) flow coastdown data obtained during the UCN4 post-core hot functional test was evaluated by comparing against the COAST code predictions. Since there is no direct core flow measurement device, experimental flow rates was estimated using the recorded data by the data acquisition system. Based on the comparison, current flow estimation method is assessed and, then an improved method is proposed.

For the simulation of combined flow transients such as locked rotor(or sheared shaft) with delayed LOOP, modifications were made to the COAST code.

From the comparison of test results with the COAST code predictions, it was shown that the COAST code predictions are conservative, and that the trends of test results are well predicted by the COAST code.

1. Introduction

Accurate prediction of the RCP coastdown flow rate behavior is very important in the assessment of the fuel performance during the flow transient where the reactor and turbine trip occurs coincidently with a loss of offsite power(LOOP)[1,2].

In UCN 4, no direct measurement devices are installed which provides actual core or reactor coolant system(RCS) flow rate. During the normal or transient conditions, various system parameters are measured and those data is available from the data acquisition system. Among the various data, differential pressures and RCP speeds can be used to estimate the flow rate[3].

In the safety analysis of KSNP, the COAST code was used to calculate the RCS flow rate during a RCP transient in a two loop, 4 RCP plant[7]. Thus, the results of the COAST code should be conservative to be applicable to the safety analysis. However, since the validation and verification of the COAST code have not been performed for KSNP, it is necessary to evaluate actual coastdown flow rate data for the validation of the COAST code. In this study, the COAST code predictions are compared against the measured data during the post core flow measurement test for UCN 4.

2. RCS Flow Measurement for UCN 4

The objectives of the post-core RCS flow measurements are to establish reference post-core RCS flow rate, to determine the post-core RCS flow rate with any combinations of RCPs (4, 3, 2 ,1 and no operating RCP cases), to collect the post-core RCS flow data during RCP transients, and to determine the validity of major RCP parameters. However, the main purpose of this test is to determine steady state RCS flow rate.

In order to better understand the RCP flow coastdown behavior, various combinations of the pump conditions which may occur during a transient(on, off, Locked Rotor and Sheared Shaft) should be considered. For this, additional tests were performed during the RCS flow measurement for UCN 4. However, the additional tests were selected to minimize the impact on the post-core hot functional test procedure and to avoid unexpected RCS component damage, additional tests are minimized as shown in Table 1. Compared to the pre-exisiting procedure, only two steps of the four pump steady conditions are added without any change in the test procedure.

The original procedure of the test[4] was modified to reflect the RCP transient flow measurement procedure.

3. Flow Rate Calculation

The steady and transient(coastdown and RCP startup) RCS flow rates are calculated using data obtained from the plant data acquisition system(PDAS) or the test data acquisition system(TDAS) during the flow measurement tests.

During the test, test data from the TDAS and PDAS are collected .

Since there is no direct measurement method for the RCS flow rate, other flow rate estimation methods should be provided for the evaluation of the test. Among the data taken from TDAS or PDAS, differential pressures and RCP speeds can be used to estimate the flow rate.

3.1 Flow Rate Calculation Using Pump Δ P Method : Since this method uses differential pressure and speed of each RCP, pump flow can be obtained without any hydraulic interference of RCS. Thus, this calculation method is more accurate than that using the steam generator Δ P. However, it requires the pump speed and the homologous curve of RCP.

The pump flow rate is calculated in the exactly reverse order of the homologous curve generation method.

In general, the homologous curves are given by the following dimensionless parameters:

$$h = \frac{H}{H_R}, \quad a = \frac{V}{V_R}, \quad v = \frac{Q}{Q_R}$$

where H : head

V : RCP Speed

Q : pump flow rate

R : rated condition

Using the homologous curve table, the pump flow rate can be obtained as follows:

$$Q = Q_R \cdot f^{-1}\left(\frac{h}{a^2}\right) \cdot \frac{V}{V_R} \qquad (1)$$

where, f^1 is the inverse function of the homologous function
The core flow rate can be estimated by summing up each pump flow rate obtained using Equation (1).

3.2 Flow Rate Calculation Using SG Δ P Method : The flow rate calculation method using steam generator differential pressure is very simple, but can provide only the loop flow rate. The pump forward and reverse flow rates cannot be estimated by this method. This method can be described as :

$$\Delta P = f\frac{L}{D}\frac{\rho}{2g_c}\frac{Q^2}{A^2} \tag{2}$$

where ΔP : steam generator differential pressure

ρ : density

f : friction factor

D : flow diameter

L : flow length

g_c : gravitational constant

Q : hot leg flow rate

A : flow area

As the friction factor is dependent on the loop conditions such as flow rate, density and temperature, the effect of these parameters on the friction resistance should be considered in the evaluation of the flow rate[8]. Since the friction resistance of primary loop except for the steam generator tube have negligible effect on the total system resistance, only the friction resistance of the steam generator tube is considered. The friction factor can be expressed as a function of Reynolds number(Blausis formula) :

$$f = \alpha + \beta \cdot Re^{-\gamma}$$

where α, β, γ are obtained from the calculation results of the FITS code[8,9].
Figure 1 shows the effect of core flow rate on the friction resistance. The calculated friction factor at a given flow rate is used in the evaluation of Equation (2). Then, the core flow rate can be obtained by the sum of two hot leg flow rates estimated using Equation (2).

3.3 Comparison of the Two Methods : The pump Δ P method can provide each cold leg flow rate and gives information of reverse flow effect. However, since this method uses the pump speed and homologous curve generated by model pump test, more uncertainties may be involved in the estimation of the flow rate. The steam generator Δ P method only uses the differential pressure between steam generator inlet and outlet for the estimation of the loop flow, however it cannot give the reverse flow information of the loop.

Comparison of the two methods can be summrized as follows :

Item	SG ⊿P	Pump ⊿P
Loop Flowrate Calculation	O	O
Pump Flowrate Calculation	X	O
Required Variable	SG ⊿P, Reference Condition(Flowrate, SG ⊿P)	Pump ⊿P, RCP Speed,Rated Conditions
Dependency on the Data	Only have dependecy on ⊿P	Highly dependent on RCP speed. Have dependecy on ⊿P
Dependency on the System	O	X

3.4 COAST code : The COAST code is designed to simulate the flow transient behavior in a two loop, four pump plant in the events where power outages to one or more pumps occur, or a pump impeller seizure occurs. The plant primary loop is represented by 7 flow paths consisting of the core, two hot legs with steam generators, and four cold legs with pumps. Momentum balance equations for each of the seven flow paths are solved in the code. The coastdown coupling between pump impeller and coolant is obtained from pump 4 quadrant test data, and are entered as input to the code to minimize analytical details required to describe the coupling. In the modeling of segment momentum balance equations, COAST intentionally omit the momentum flux and gravity head terms and assumes constant pressure. As a result, use of the COAST program without gravity head effects, and without variable density parameters in the momentum equations will be of limited accuracy when used in a core thermal assessment near the end of coastdown.

The current COAST code does not have an option for the combination of one pumps locked rotor and remaining three pumps coastdown when LOOP occurs. To improve the simulation capability of the COAST code, some modification in main program and subroutines are made without any change of code model and structure. With this modification the COAST code is applicable to the simulation of the combined events such as locked rotor(or sheared shaft) with delayed loss of offsite power(or RCP coastdown).

4. Results

After calculating the flow rates of each test case using both the SG and the pump differential pressure data, the calculated flow rates are compared with each other and also with the COAST code predictions.

Figure 2 shows the difference in the normalized flow rates estimated by the two methods during the four pump coastdown transient. The calculated flow rates by the two methods are almost the same except at the beginning of the pump coastdown. The difference at the beginning of coastdown is supposed to be the effect of uncertainty of RCP homologous data used in the RCP ΔP method.

Figures 3 and 4 show the comparison of normalized flow rates in the three pump and two pump conditions. The pump parameters used in these cases are the same as those in the four pump coastdown case shown in Figure 2. The three and two pump coastdown flow rates calculated using the two methods are almost the same.

Figure 5 shows the comparison of the results of test step 2 in Table 1 with the results of the COAST code simulation. The prediction of the COAST code shows more conservative flow rates than those of the test results.

Figure 6 shows the comparison of the results of test step between 7 and 8 in Table 1, that was designed to simulate locked rotor with delayed LOOP, with the results of the COAST code simulation. As can be seen in the figure, the COAST code conservatively predicts the RCS flow rate.

5. Conclusion

After the UCN 4 post-core hot functional test, the core flow rate was estimated using the test data obtained from TDAS and PDAS. Two flow rate calculation methods, namely RCP ΔP and SG ΔP methods, produce almost identical results in high flow ranges. If some corrections are made in the estimation of the core flow using SG differential pressure, the calculated results can be used in the prediction of loop and core flow rate in low flow range. For the prediction of pump flow rate or the effect of reverse flow, the pump ΔP method using homologous data can be utilized.

From the comparison of test results with the COAST code predictions, it can be seen that the COAST code predictions are conservative and that the measured trends are well predicted by the COAST code. For the simulation of the one pump coastdown with delayed three pump coastdown, modifications were made to the COAST code. It was demonstrated that the results of the COAST simulations for the case are conservative compared to the test results.

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6. Technical Specifications for UCN 3 and 4.
7. COAST(PC) CODE SVVR, 00000-SS-VV-004, Revision 00
8. CA-76-159, "SYSFLOW3 Code Approval", S. J. Bach, Nov. 15, 1976.
9. CENPD-71, "REVEL, A Computer Code to Calculate Nozzle Pressure Drop", F.J. Staron and R.H. Vickerman

Table 1. Revised RCS Flow Measurement Test

Step (in original procedure)	Status	Active Pump	Steady Test Required	Coastdown Test
1	4 Pump Steady	1A, 1B, 2A, 2B	O	4 Pump Coastdown (4 pump coincident trip)
2	4 Pump Coastdown			
3	0 Pump Steady		O	
4	3 Pump Steady	1A, 2A, 2B	O	1 Pump Coastdown 2 Pump Coastdown in the same loop (2 pump coincident trip)
5	2 Pump Steady	2A, 2B	O	
*	0 Pump Steady		O	
*	4 Pump Steady	1A, 1B, 2A, 2B	O	2 Pump Coastdown in the opposite loop (2 pump coincident trip) 1 Pump Coastdown 1 Pump Coastdown
6	2 Pump Steady	1B, 2B	O	
7	1 Pump Steady	1B	O	
*	0 Pump Steady		X	
*	4 Pump Steady	1A, 1B, 2A, 2B	O	1 Pump Coastdown 3 Pump Coastdown (3 pump coincident trip)
*	3 Pump Steady	1A, 2A, 2B	O	
*	0 Pump Steady		O	
8	4 Pump Steady	1A, 1B, 2A, 2B	X	

Note : * means newly added test steps

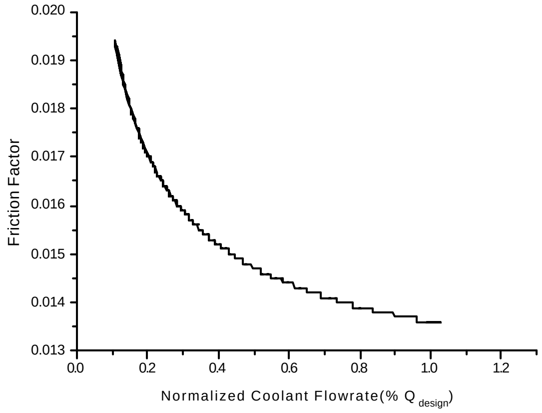

Figure 1. The Effect of Core Flowrate on the Friction Resistance

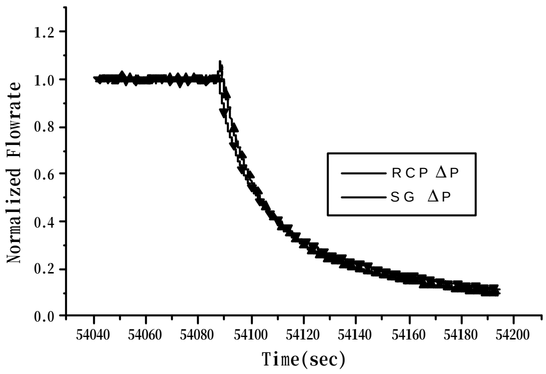

Figure 2. Comparison of Normalized flow rates at 4 Pump Coastdown

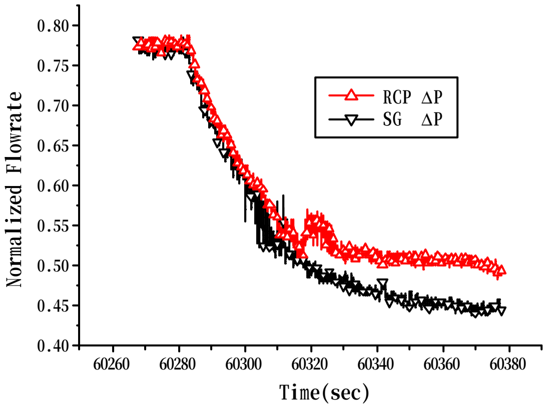

Figure 3. Comparison of Normalized flow rates at 3 Pump Condition

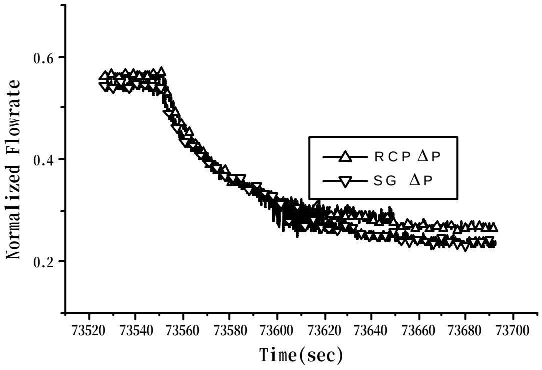

Figure 4. Comparison of Normalized flow rates at 2 Pump Condition

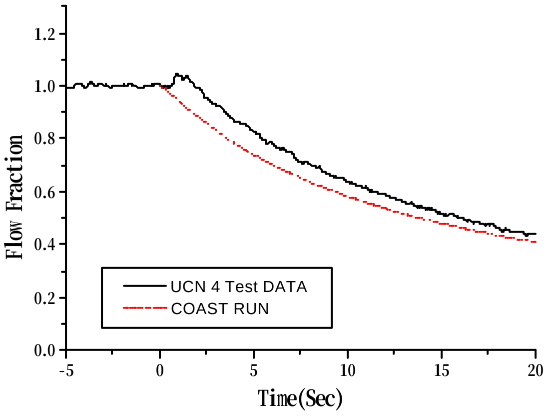

Figure 5. Comparison of Test Result with COAST at 4 Pump Coastdown

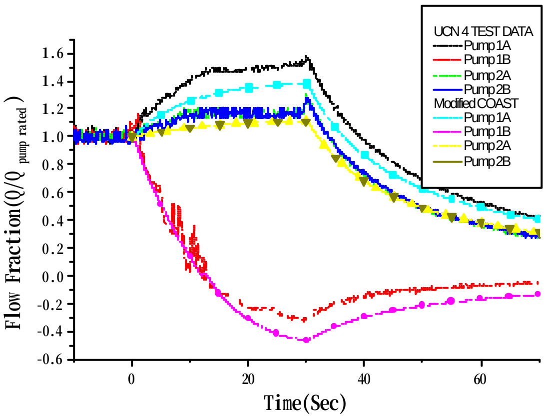

Figure 6. Comparison of Test Result with COAST at 1-3 Pump Coastdown