Comparison of Pump Performance Predicted by MARS-KS and Analytical Model

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1. Introduction

1.1 Pump Performance in Safety-related Systems

Safety-related systems in nuclear power plants (NPPs) perform the safety functions when required. One of the most important safety functions is the heat transport function. The systems that function as heat transport can be classified into passive systems using passive components and active systems using active components. Passive heat transport systems such as the passive residual heat removal system (PRHRS) of the SMART100 [1] transport heat by natural circulation. On the other hand, active heat transport systems such as the shutdown cooling system (SCS) of the APR1400 [2] transport heat by forced convection. Most active heat transport systems consist of pumps to supply the flow rate, valves to control the flow rate, and heat exchangers to transport the heat. Therefore, the performance of the active heat transport systems can be represented by the performance of the pumps, valves, and heat exchangers.

In this study, the pump performance is focused on among the factors which represent the performance of the active heat transport systems.

1.2 Limitation of Modeling Pump as Boundary Condition

Licensees of NPPs perform the thermal-hydraulic analysis using the system thermal-hydraulic analysis code to show that the safety of NPP is guaranteed in transient and accident situations. In most the thermal-hydraulic analyses, safety-related pumps are treated as boundary conditions and not as component models [3-4], except for the reactor coolant pump attracting attention with coast down after their trip [5]. This comes from the assumption that the pump performance can be expressed as a certain flow rate and differential pressure. However, it may not be appropriate to simply model pump performance with a certain flow rate and differential pressure. This is because, in the actual situation, the flow rate and differential pressure would vary in real time depending on the operating environment that can be represented as the combination of the pump characteristic curve and the system resistance curve. For this reason, it is acceptable to model the pump as a boundary condition only when the model is proven to be conservative.

1.3 Comparison of Pump Performance

This study is a preliminary study to investigate whether the pump model in the MARS-KS can be applied to the thermal-hydraulic analysis instead of treating the pump as a boundary condition. The MARS-KS is one of the representative system thermal-hydraulic analysis codes, and the pump model in the MARS-KS is designed to reflect the actual operating characteristics of the pump. In this study, the pump performance predicted by the MARS-KS 1.4 was compared with the one predicted by the analytical model for a generalized system with a single operated pump. The general description, the specific prediction methods, the results, and the conclusion are presented.

2. Methods and Results

2.1 Brief Description of the Single Pump Problem

In this study, a generalized closed-loop was considered to compare the results of the pump performance predicted by the MARS-KS and analytical model. The system consisted of a pipe, a pump, and accessories. In addition, The operating fluid of the system was water in the state of 0.5 MPa 314.9 K based on the pump suction side, and no two-phase flow occurred. The pump was operated at the rated speed, and the system was in steady state condition.

The characteristic curve of the pump mounted on the system was modeled as the quadratic equation below as

$$H/H_R = -0.7(Q/Q_R)^2 + 1.46 \tag{1}$$

where H and Q was the differential pressure and the flow rate, respectively, and the subscript, R, means rated condition. The coefficients of each term in the equation was chosen in the consideration of general characteristics of centrifugal pump [6]. The major specification of pipe and pump were shown in table I.

Table I: The Major Specification of the Pipe and the Pump

The length of the Pipe (m)	21.0
The Diameter of the Pipe (mm)	356
The Wall roughness of the Pipe (mm)	1.778
The Rated Flow of the Pump (m^3/s)	1.500
The Rated Pressure of the Pump (m)	20.0
The Rated Speed of the Pump (RPM)	360

Five system resistances cases were determined to cover the various operating points of the pump. The five cases included the pump's rated, shut-off, and run-out operating point. Table II showed the determined five cases with the pump operating points, Q/Q_R and the system form loss factor, $\sum K_i$.

Table II: Five Cases

Case	Q/Q_R	$\sum K_i$
Case 1	0.28	30.0
Case 2	0.48	8.00
Case 3	0.64	3.00
Case 4	0.80	0.90
Case 5	0.92	0.00

The presented characteristic curve and system form loss factor were applied to both the MARS-KS and the analytical model.

2.2 Pump Performance Prediction by MARS-KS

The characteristic curve applied to the MARS-KS follows equation 1, and 11 point data was inputted for the characteristic curve. In the MARS-KS, the pump operating point was calculated with a given characteristic curve and given volumetric properties. The calculated pump pressure was used for the momentum equations in the MARS-KS, and the volumetric properties were recalculated from the momentum equations [7].

To implement the five system cases to MARS-KS, the form loss factor at junction component was controlled. The equation for the form loss factor at junction component applied to the MARS-KS was given by

$$K = A + B \cdot Re^{-c} \quad (2)$$

Where K, A, B, and C was the form loss factor, the coefficient independent on the Reynolds number, the coefficient dependent on the Reynolds number, and the exponent coefficient of Reynolds number [6]. Since the coefficient dependent on Reynolds Number was significant in the low Reynolds number region, it is not considered in this problem with the high Re_{rate}, 1.0E5.

2.3 Pump Performance Prediction by Analytical Model

In order to establish an analytical model, it is necessary to define the characteristic curve of the pump and the resistance curve of the system. The characteristic curve followed equation 1 as it is. The resistance curve of the system was considered as below.

The resistance curve of the system was formulated in proportion to the square of the flow rate, and the sum of the system resistance coefficient derived from the pipe and accessories as

$$S.R.C.(Q) = R_{sys} \cdot \frac{Q^2}{2gA_{pipe}{}^2} \quad (m) \quad (3)$$

where

$$R_{sys} = f\frac{l}{D_h} + \sum K_i$$

In the equation above, $S.R.C.$ and R_{sys} means the resistance curve of the system and the resistance curve of the system, respectively. In addition, Q, A_{pipe}, g, f, l, D_h, and K_i is the values of the flow rate, the area, the gravity constant, the friction coefficient, the length of the pipe, the hydraulic diameter of the pipe, and the form loss factors, respectively. The system form loss factor, $\sum K_i$, was controlled to match the five cases as table II. The friction coefficient was chosen from the moody chart [8].

2.4 Results of Pump Performance Prediction

The performance of the pump was expressed by the flow rate and differential pressure at the operating point. For the five cases, The flow rates and differential pressures predicted by the MARS-KS and analytical model were shown in table III.

Table III: The Relative Deviation of Pump Performance

Case	$\Delta Q/Q_{AM}$ (%)	$\Delta H/H_{AM}$ (%)
Case 1	0.08	-0.01
Case 2	-0.20	0.01
Case 3	-0.43	0.03
Case 4	-0.79	0.74
Case 5	-1.019	1.592

Generally, the results between the MARS-KS and analytical model showed nearly perfect consistency, but there was a case of which deviation was over than 1.0%. The deviation of case 5 was -1.0 %, 1.6% for the flow rate and the differential pressure. The case 5 simulated the run-out operating point, and considered only the resistance coefficient derived from the pipe. Since the resistance coefficient derived from the pipe has reading error of friction coefficient, it is reasonable that the biggest deviation occurred at case 5. Also, considering the uncertainty from reading error, the deviation of the case 5 was able to be acceptable.

3. Conclusions

This study was conducted as a preliminary study to investigate the applicability of the pump model in the MARS-KS to the deterministic thermal-hydraulic analysis, instead of modeling the pump as boundary conditions. It can be summarized and concluded as

- The pump performance predicted by the MARS-KS was compared with the one predicted by the analytical model.

- The pump performance predicted between the MARS-KS and the analytical model showed nearly perfect consistency, except for case 5.

- The deviation of case 5 was -1.0 %, 1.6% for the flow rate and the differential pressure, and it was able to be acceptable considering the uncertainty.

- In a wide range of pump operation, the pump performance prediction in MARS-KS was reasonable.

Based on this study, in the case where the pumps are operated in parallel or in series, further studies will be conducted to determine whether the pump model the MARS-KS is still valid.

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