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Improvement in Performance Evaluation Factors for a Reactor Coolant Pump (RCP) Test

Y. J. Cho, Y. S. Kim, S. Cho, S. Kim, B. U. Bae, H. J. Chung, B. D. Kim, Y. J. Youn, J. K. Park, H. S. Choi,
W. J. Jeon, T. S. Kwon, C. H. Song

Korea Atomic Energy Research Institute, 111 Daedeok-daero, 989 Beon-gil, Yuseong-gu, Daejeon
**Corresponding author: yjcho@kaeri.re.kr*

1. Introduction

In 2012, the Korea Atomic Energy Research Institute (KAERI) constructed a Reactor Coolant Pump (RCP) Test Facility (RCPTF). The main target of the RCPTF is the RCP under the operating condition of an Advanced Power Reactor 1400 MW (APR1400). Therefore, the design values of the RCPTF are 17.2 MPa, 343 ^{o}C, 11.7 m^3/s, and 13 MW in maximum pressure, temperature, flow rate, and electrical power, respectively. In the RCPTF, various types of tests can be performed, including a hydraulic performance test to acquire a H-Q curve as well seal transient tests, thrust bearing transient test, cost down test, and an NPSHR verification test [1].

After a commissioning startup test was successfully performed [2], mechanical structures were improved including a flow stabilizer and variable restriction orifice. In addition, the improvements were made in the signal process of the performance evaluation factors such as the flow and pressure pulsation. This paper focuses on the latter.

2. RCP Test Facility

Fig. 1 shows an overview of the RCPTF. The length of the main pipe from the discharge of the RCP to the opposite end is about 31 m. The diameter of the main pipe is 0.914 m corresponding to the cold leg of the APR1400. A pipe of 0.762 m diameter is used where the venture flow meter and the RCP are connected.

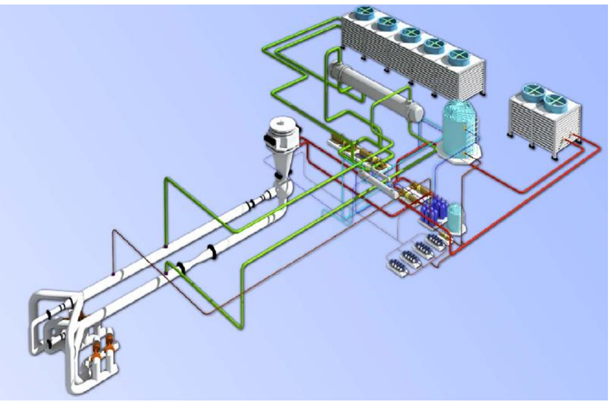

Fig. 1. Overview of the RCPTF

A heat exchanger with 20MW of heat capacity was installed to remove the heat from the RCP through the main loop of the RCPTF. An additional heat exchanger is also installed to extract the heat in the component cooling water for the seal injection, air cooler in a motor, and so on. The system pressure is controlled using a feed and bleed method using charging pumps and pressure control valves.

The main measurement parameters are the main flow rate, pump head, system pressure, temperature, motor power, and shaft speed. For the endurance test, the pressure pulsation, frame vibration, and shaft vibration are also measured. The main flow rate is measured by a standard venture flow meter installed at the upstream of the RCP suction. Most of measured parameters have the success criteria according to the type of test.

The APR1400 RCP is operated with a constant RPM so that the flow area should be changed to control the main flow rate for the hydraulic performance tests. The RCPTF gained the controllability of the main flow rate by the development of a Variable Restriction Orifice (VRO), while the minimum flow rate was obtained. When a high main flow rate is required, operators can control the butterfly valves and the globe valves that are separately installed at the Y-branch. It is possible to accurately control the main flow rate using the globe valve because its CV value is less than 1/10 of the butterfly valve.

3. Compensation of Static Hole Error

The RCPTF uses a standard type of venture flow meter designed by ASME MFC-3M-2004 and ISO 5167-4 [3, 4]. The mass flow rate in the standard venture flow meter is defined by

$$q_m = C_D \varepsilon \frac{\pi}{4} d^2 \frac{\sqrt{2\Delta p \rho}}{\sqrt{\beta^2 - 1}} \tag{1}$$

In Eq. (1), CD means a discharge coefficient defined as the ratio of measured mass flow rate and the theoretical one. The discharge coefficient can be usually acquired by a calibration as a function of the Reynolds number.

The venture flow meter in the RCPTF was calibrated at Colorado Engineering Experiment Station Inc. (CEESI) in Idaho, USA. CEESI uses a natural gas as a working fluid while the RCPTF uses water. Therefore, there must be discrepancy due to the different working fluid in the CEESI and the RCPTF.

The concept of the static hole error was introduced to compensate the discrepancy due to the different working fluid. The static hole error defines the effect in which the pressure tap of a finite size cannot measure the pressure that would have been measured using an infinitely small pressure tap. Because of the static hole error, the measured pressure is always higher than the theoretical static pressure that would have occurred if the pressure tapping hole had not been present.

Franklin and Wallace measured the static hole error and suggested a correlation as a function of the wall shear stress, viscosity, density, and hole diameter [5]. Harris quantified the effect of static hole error in the water and gas, respectively. In addition, he suggested a correlation to estimate the difference between the discharge coefficient measured in water and water [6]. In Harris's paper, the tapping hole Reynolds number (Re_{tap}) is defined as

$$\mathrm{Re}_{tap} = \frac{u_\tau d_{tap}}{\nu} \tag{2}$$

where, u_τ, d_{tap}, and ν mean the friction velocity, diameter of the tap hole, and kinetic viscosity, respectively. The, the ratio between an increase in measured pressure (e) and the wall shear stress (τ) can be formulated as a function of the tapping hole Reynolds number.

$$\frac{e}{\tau} = f\left(\mathrm{Re}_{tap}\right) \tag{3}$$

Then, the increase of the discharge coefficient (C_D) due to the static hole error is expressed as

$$\Delta C_D = \frac{0.015 f\left(\mathrm{Re}_{tap,throat}\right) - 0.012\beta^4 f\left(\mathrm{Re}_{tap,up}\right)}{8\left(1-\beta^4\right)} \tag{4}$$

where β is the diameter ratio of the venture flow meter. Because the static hole error is different in the gas and water, the difference can be defined as

$$\Delta C_{D,gas} - \Delta C_{D,water} = \frac{0.015 f^*\left(\mathrm{Re}_{tap,throat}\right) - 0.012\beta^4 f^*\left(\mathrm{Re}_{tap,up}\right)}{8\left(1-\beta^4\right)} \tag{5}$$

Harris suggested the best fit of f^* for a standard venture as

$$f^*\left(\mathrm{Re}_{tap}\right) = \begin{Bmatrix} 7.162 - 8.839e^{-0.00007\mathrm{Re}_{tap}} & \text{for } \mathrm{Re}_{tap} > 3000 \\ 0 & \text{for } \mathrm{Re}_{tap} \le 3000 \end{Bmatrix} \tag{6}$$

Finally, the discharge coefficient with the compensation of static hole error and discrepancy in the working fluid can be calculated as

$$C_{D,water} = C_{D,gas} - \frac{0.015 f\left(\mathrm{Re}_{tap,throat}\right) - 0.012\beta^4 f\left(\mathrm{Re}_{tap,up}\right)}{8\left(1-\beta^4\right)} \tag{7}$$

Using Eq. (7), the discharge coefficient calibrated in CEESI was compensated as shown in Fig. 2. The discharge coefficient decreased by 0.003 to 0.016 according to applying the static hole error.

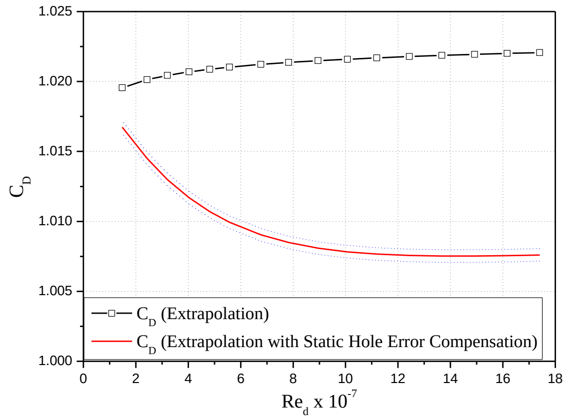

Fig. 2. Discharge coefficients before and after compensation

The reduction of the discharge coefficient resulted in a decrease in the mass flow rate in the hydraulic performance tests. In particular, 1.33 % of the mass flow rate decreased at the maximum Reynolds number during a hot performance test, as shown in Fig. 3. The pump head was non-dimensionalized because of the agreement of the data production for the RCP test data.

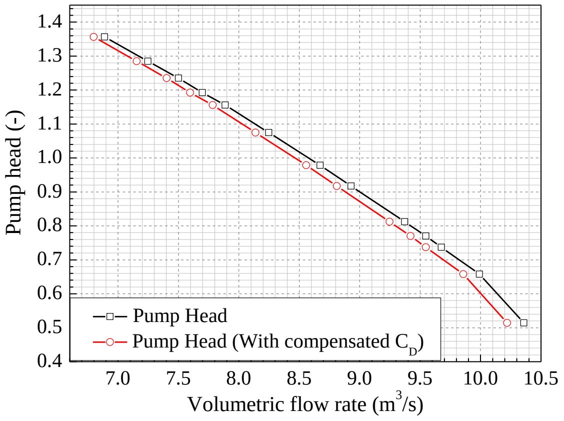

Fig. 3. H-Q curve in hot performance test before and after compensation

4. Evaluation of Pressure Pulsation Data

During the running of the RCPs, the generation of the pressure pulsation is inevitable owing to the impingement of a wake flow on the diffuser vanes. The wake flow generates frequencies that correspond to the blade passing frequency (BPF) that can be varied according to the number of blades and the rotating speed of the RCP. With the wake flow, a vortices at downstream of the trailing edge are also responsible for the pressure pulsation. Therefore, the measuring data of the pressure pulsation is an indicator to estimate whether the design and fabrication of the casing, impeller, and diffuser of the RCP are proper or not.

In the RCPTF, three sensors for the pressure pulsation were installed at different locations: upstream of the pump suction and two different points at the downstream of the pump discharge. Measured data were converted by fast Fourier transform (FFT), and the root mean square (RMS) values at 1 to 8 times the BPF were recorded.

To estimate the effect of fluid temperature on the pressure pulsation, the pressure pulsation was measured with a slight increase in fluid temperature of about 10 °C to 15 °C per 1 hour. During the measurement, a constant mass flow rate was maintained. Fig. 4 shows the measured pressure pulsation at the first BPF with the increase of fluid temperature. As shown in the figure, the pressure pulsations measured at three different points show peaks at a similar temperature range of 153 °C and 281 °C. This trend was also shown in other performance tests. This phenomenon is caused by an acoustic resonance that is dependent on the design of pipes and mechanical components in the RCPTF.

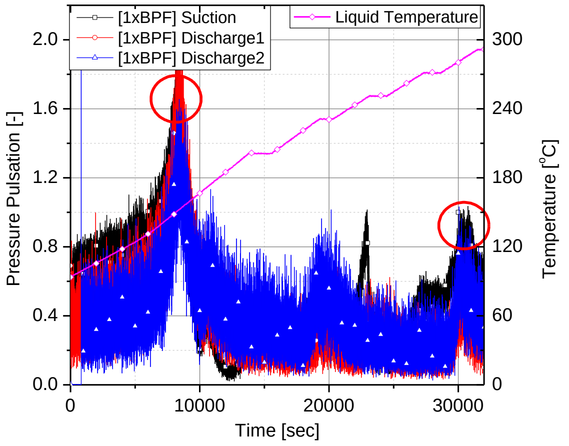

Fig. 4. Pressure pulsation at 1st BPF

A harmonic resonance frequency (f_n) can be calculated using the assumption of an open pipe as

$$f_n = \frac{a \cdot n}{L \cdot 2}. \tag{8}$$

In Eq. (8), *a*, *n*, and *L* mean the acoustic velocity, the order of harmonics, and the characteristic length of the pipe, respectively. The characteristic length of the pipe was assumed to be equal to the length from the discharge of the RCP to the center of the U-bend located at the opposite end of the loop.

Fig. 5 shows the harmonic resonance frequencies calculated by Eq. (8). The 5th order harmonics at 153 °C and the 7th order harmonics at 281 °C coincide with the first BPF, which is 120 Hz. Thus, it is reasonable to conclude that the peaks at 153 °C and 281 °C in Fig. 4 are caused by the harmonic resonance.

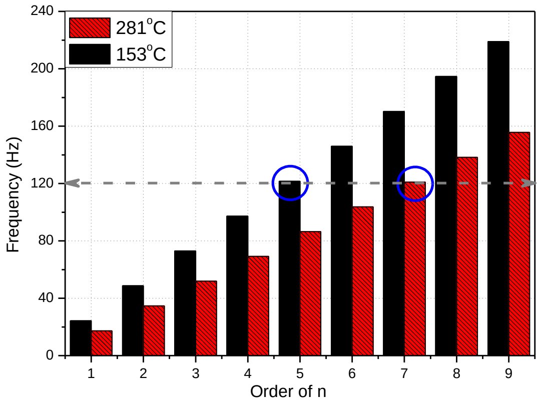

Fig. 5 Harmonic resonance at 153°C and 281°C

To prevent the acoustic resonance, mechanical devices are required, such as a pulsation damper at the pump discharge or a suction stabilizer at the pump suction. However, the installation of the mechanical devices may cause a modification of the pump characteristic curve. Therefore, it is appropriate to estimate the temperature range that can cause acoustic resonance and to operate out of the specific temperature range. By excluding the effect of acoustic resonance on the pressure pulsation data, it is possible to acquire more realistic pressure pulsation data in which the increase due to the effect of acoustic resonance is minimized.

5. Conclusions

In the RCPTF in KAERI, the performance tests and various kinds of transient tests of the RCP were successfully performed. The accuracy in the measurement of the flow rate was improved by compensating the static hole error so that the effect of the difference between the working fluids in the RCPTF and the calibration facility was removed.

The unexpected increase in the measurement of the pressure pulsation at the specific temperature range was examined, and it was clarified that the acoustic resonance may cause the increase.

ACKNOWLEDGMENTS

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