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Domestic activity for technical development of the APR1400's RCP performance test

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1. Introduction

Test facility for performance verification of an APR1400's Reactor Coolant Pump (RCP) had been constructed in KAERI site at the end of 2012. The thermal hydraulic and electric capability of the RCP test facility (RCPTF) covers up to 18.5 MPa, 343 ^{o}C, 11.7 m^3/s, and 14.0 MW in the design pressure, temperature, flow rate, and the maximum electric power, respectively. In 2013, commissioning test had been performed to verify its designed capability, followed by several modifications in the RCPTF including signal processing and control logic to enhance verification and evaluation capability of the RCP performance. After finishing the commissioning and modification of the RCPTF, type test for the new-type RCP had been performed successfully. In addition, 4 RCP production tests of the commercial nuclear power plant were completed in 2014, and in this year, 2015, KAERI is carrying out the RCP production test for the rest of the RCP. In this paper, several technical issues developed in the 2013 and the type test's method and results will be described.

2. RCP Test Facility

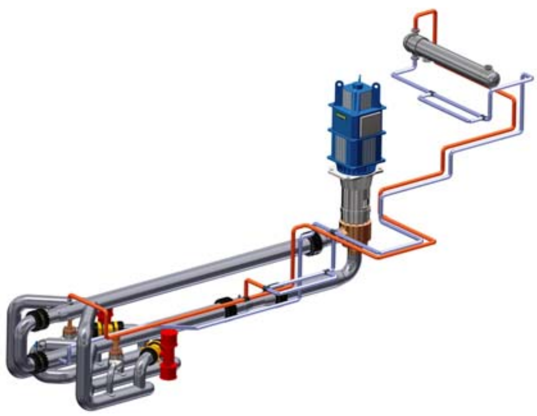


Fig. 1 Graphical description on the RCPTF

The length of main pipe of the RCPTF from the discharge nozzle of the casing to the opposite end is up to 31 m. Figure 1 shows a bird-eye view of the RCPTF. The diameter of the main pipe is 0.914 m with considering of cold leg size of APR1400. To control the flow rate in the main pipe, a Variable-type Restriction Orifice valve (VRO) and two globe valves are installed in the main and subsidiary pipes, respectively.

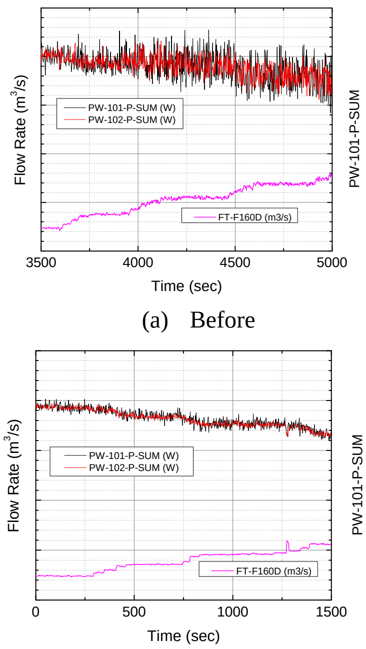
The system pressure can be controlled by a feed and bleed method using charging pumps and pressure control valves. A main heat exchanger with 20MW capacity is installed to remove the heat from the RCP. An additional heat exchanger is used to remove the heat from the auxiliary system of the RCP such as letdown cooler, high-pressure leakage cooler, high-pressure cooler, oil cooler and motor cooler.

Main measurement parameters are flow rate (QP) and head (HP) of RCP, 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 venturi flow meter installed at the upstream of the RCP casing.

3. Technical Development for the Performance Test

From the commissioning test, KAERI found several items need to be modified or upgraded to optimize the verification & evaluation capability of RCP test. In this section, related modified or upgraded technical items will be described.

3.1 Flow disturbance



(a) Before

(b) After

Fig. 2 Comparison of data with the flow straightener & VRO

To control the RCP flow rate in the main pipe, two subsidiary pipes with 4 control valves are attached to the main pipe. The flow disturbance in the main pipe is mainly due to the subsidiary flow from the sub-pipe. Moreover, main measuring parameters including RCP flow rate and shaft vibration were affected severely by the flow disturbance, especially, in the upstream of the venturi flow meter.

As a counter measure for this flow disturbance, KAERI devised the VRO and the flow straightener and installed them in the lower part of the main pipe. Flow stabilizing performance has been verified by comparing the characteristic data measured at before and after the installation of the VRO and the flow straightener. Figure 2 shows an example of the comparison. The current VRO can control the RCP flow rate from 6.5 m^3/s to 9.8 m^3/s. For a higher RCP flow rate up to 10.5 m^3/s, globe & butterfly valve installed in the subsidiary pipe can be used.

3.2 RCP flow rate

The venture flow meter installed in the lower main pipe, upsteam of the RCP casing, is a standard type of venture tube designed according to the ISO 5167-4 and ASME MFC-3M-2004 [1, 2]. Generally, a discharge coefficient of venture flow meter is a function of Reynolds number and can be acquired by the calibration test. The calibration of the venture flow meter of the RCPTF was performed at Colorado Engineering Experiment Station Inc. (CEESI) in Idaho, USA. CEESI uses a natural gas as a working fluid while the RCPTF uses water [3].

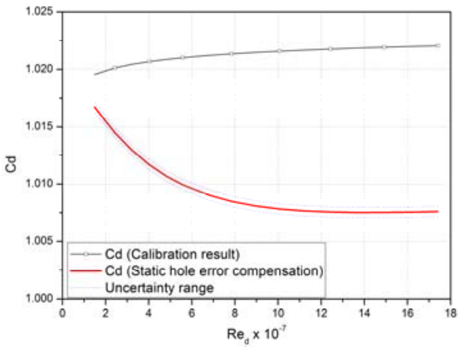


Fig. 3. Compensation of static hole error in discharge coefficient

To compensate the discrepancy due to the working fluids, KAERI introduces the concept of static hole error. It means an effect that pressure tap of finite size may not measure the pressure which can be measured an infinitely small pressure tap. Harris quantify the static hole error in the gas and water respectively, and suggested the correlation to calculate the difference between the discharge coefficient measured in gas and water in Eq.(1) [4].

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

Figure 3 shows the compensation result. The discharge coefficient was reduced by 0.003 ~ 0.016. This reduction in the discharge coefficient resulted in the decrease of the flow rate by 1.33 % at the maximum Reynolds number.

3.3 Pressure pulsation

With an operation of RCP, a pressure pulsation in the suction and discharge main pipes is generated. The pressure pulsation is mainly due to the impingement of wake flow in the diffuser vanes. Moreover, the wake flow creates characteristic frequencies corresponding to the Blade Passing Frequency (BPF). This characteristic frequency is varied by the number of blades and the rotating speed of a RCP. The blade number and rotating speed of the APR1400's RCP are 6 blades and 20 Hz, respectively.

During a pre-test period, KAERI observed that pressure pulsation in the pipe is varying with a fluid temperature and have a peak at the specific temperatures of 153 ^{o}C and 281 ^{o}C. This change of the pressure pulsation is responsible for an acoustic resonance that is caused by design characteristics of the pipe.

A harmonic resonance frequency (f_n) was calculated to evaluate an effect of an acoustic resonance. Finally, KAERI found that the calculated harmonic resonance frequencies at the temperatures of 153 ^{o}C and 281 ^{o}C are in the range of 121.0 Hz to 121.6 Hz which is similar frequencies with the BPF of APR1400's RCP.

The acoustic resonance affects a vibration characteristic of the pipe and the rotating shaft. To prevent the resonance effect, the hot & cold hydraulic performance tests of RCP are carried out at the different temperature range.

3.4 Vibration

A loop vibration characteristic due to fluid flow can affect the vibration behavior of the RCP such as the frame and the rotating shaft. In order to improve an evaluation accuracy of the RCP vibration data, KAERI performed a frequency analysis of the RCPTF under several kinds of load combinations. Three kinds of analysis were performed as follows:

(1) Frequency measurement & analysis under operating condition
(2) Natural frequency analysis under wet condition
(3) Natural frequency analysis under dry condition

From the measurement and analysis, three characteristic frequencies were found such as 20 Hz, 120 Hz, and 200 Hz. The 20 Hz and 120 Hz are originated from the RCP vibration and the 200 Hz was from the main pipe [5].

4. RCP Type Test (500 hr Test)

The type test shall be performed to verify a new-type (production-type) RCP in respect of the thermal-hydraulics and mechanical stability. A series of steady & transient tests were conducted to demonstrate the RCP capabilities. Doosan Heavy Industrial Company manufactured the production-type RCP. The followings are described test items of the 500 hr type test:

(1) Motor No Load test: Uncoupled shaft, No flow in the loop,
(2) Hydraulic Performance test: Cold & hot condition with the variation of RCP flow rate,
(3) Stop-Start test: minimum 30 cycles at various phases ,
(4) NPSHR Verification test: With the variation of RCP flow rate at relatively low pressure condition,
(5) Coastdown test: At rated condition,
(6) Runout test: At runout flow rate with cold condition, more than 50 hours operation,
(7) Continuous Operation test: At rated condition, more than 375 hours continuous operation,
(8) Seal Transient test: At rated condition, sub-divided into 4 categories with respect of the status of seal injection & component cooling water & RCP running,
(9) Thrust bearing Transient test: At rated condition with loss of cooling water.

Total accumulated time for the type test was about 714 hours. Major measurement parameters are listed below:

(1) Performance data: flow rate, head, BHP, RCP efficiency, vibration level
(2) System parameters: pressure, temperature, Pressure pulsation, main cooler temperature & flow rate, CCW temperature & flow rate, Seal injection temperature & flow rate, feed & bleed flow rate & temperature
(3) RCP: Bearing temperature, shaft rotation speed & vibration level, frame vibration level, noise level (at NPSHR test), oil temperature, HP cooler temperature, HP & LP leakage flow rate & temperature, inter-seal temperature & pressure, recirculation flow rate
(4) Motor: Stator winding temperature, bearing temperature, vibration level

NPSHR verification test is performed to verify occurrence of the cavitation and observe the vibration level at a low system pressure condition. There are two different methods to perform the NPSHR test. First method is to adjust of the flow rate and system pressure with the constant system temperature condition. Second method is to adjust the temperature and flow rate with the constant pressure condition. In the present type test, the former method was adopted for the NPSHR verification test due to the fact that a controllability of the system pressure is simpler than that of the temperature.

The seal transient test is conducted to demonstrate that the shaft seal system can meet the design requirement. The test is composed of four kinds of sub-tests. The seal transient test-I simulates a loss of seal injection with RCP running, and the seal transient test-II simulates a loss of seal injection with RCP idle. In the seal transient test-III, a loss of seal injection and cooling water to HP cooler simultaneously are simulated with RCP running, and the seal transient test-IV simulates a loss of seal injection and cooling water to HP cooler simultaneously with the RCP idle.

5. Conclusions

In the present paper, the technical activities for the development of the verification test of APR1400's RCP are described. KAERI has completed the full set of technology development, prerequisite for the RCP verification test, and now on the way to perform a test for the sealing capacity of the seal assembly during the Station Block Out (SBO) condition of APR1400.

ACKNOWLEDGMENTS

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