Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 22-23, 2025

Water Level Measurement System Based on Optical Fiber Sensors for Application of Multi-Unit Small Modular Reactors

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***Keywords :** water level measurement, optical fiber sensor, wavelength division multiplexing, Multi-unit SMR

1. Introduction

In 2020, the U.S. Nuclear Regulatory Commission (NRC) has approved the design certification of small modular reactor (SMR), i.e., NuScale which is based on integral pressurized water reactor type [1]. Due to its compact size and design characteristics, SMRs are being developed in many countries to address the increasing energy demand with non-electrical applications such as district heating, desalination, hydrogen production, industrial process heat supply and so on [2].

SMR technologies aim for cost efficiency through modularization with shorter construction schedules than those of conventional nuclear power plants [3]. Moreover, SMRs can generate the desired power output by installing multiple reactor modules within a single site. Therefore, if multiple reactor modules are installed at a single site, it is required an alternative method for simultaneously measuring essential parameters (such as level, temperature etc.) from a single the main control room (MCR) in preparation for design-basis accidents and other scenarios.

In this paper, we present a water level measurement system based on optical fiber sensors (i.e., sensing units) to simultaneously monitor essential parameters for multi-unit SMRs.

2. Water Level Measurement System for Multi-Unit SMRs

2.1 Principle of Water Level Measurement

The water level measurement is based on the Fresnel reflection at the end facet of sensing unit (SU). The change in the surrounding medium of SU induces the change of reflected optical power, and the related Fresnel coefficient (R_m) is represented as below [4].

$$R_m = \left(\frac{n_f - n_m}{n_f + n_m}\right)^2 \tag{1}$$

Here, n_f and n_m are the refractive indices of the optical fiber and the surrounding materials (i.e., air and water), respectively. The approximate values of optical fiber (n_f), air (n_{air}), and water (n_{water}) are 1.4492, 1.0002, and 1.3152, respectively. Based on the above equation, the calculated Fresnel reflection coefficients in the air and water are 3.36% and 0.24%, respectively. Without consideration of the background noise power, the reflected power difference between at the air and water is about 11.6 dB [5]. Thus, by measuring the reflected optical power spectrum in both air and water, the presence of water can be detected at the SU's installation location.

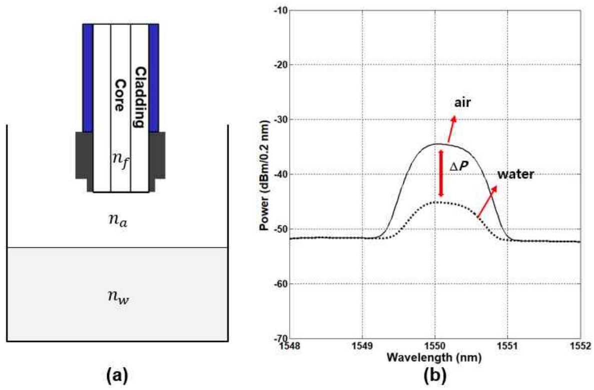

Fig. 1 Fresnel Reflection powers (a) Schematic of sensing unit (b) Measured optical spectra

Fig. 1 (a) shows the schematic of the SU, which is a commercial fiber optic patch-cord including standard LC/PC type connectors. As mentioned above, the reflection power is changed according to the refractive index of materials. These measured optical spectra are shown in Fig. 1 (b). The power ratio of two optical signals at the center wavelength was about 10.6 dB, which is 1 dB smaller than the prediction using Equation (1) due to background noise.

2.2 Architecture of Water Level Measurement System

The architecture of the proposed water level monitoring system is shown in Fig. 2. It consists of a reflectometer for the reflected optical power spectra measurement at the MCR, a single mode fiber (SMF) for transmission media, an arrayed waveguide grating (AWG) for channel multiplexing/de-multiplexing and sensing units for the sensing the water presence.

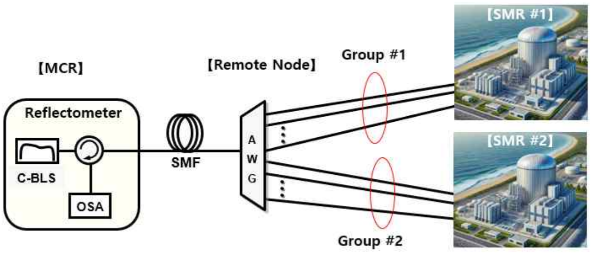

Fig. 2. Architecture of water level measurement system.

The Reflectometer comprises a Broadband Light Source (BLS) for seeding Amplified Spontaneous Emission (ASE) light to the optical fiber sensors (SU), an optical spectrum analyzer (OSA) for detecting the reflected signal, and an optical circulator (OC) for separating transmission and detection part. It determines the water level based on the information delivered from the installed pool. Next, the AWG plays an important role of channel multiplexing/demultiplexing the ASE lights for multiple optical fiber sensors in the pool of SMR. Moreover, the AWG can be used to distinguish wavelength bands for multi-unit SMRs such as group #1 and group #2.

Finally, the SUs are installed vertically in the pool where each sensing unit represents a specific water level as shown in Fig. 3, according to the assigned group number. It should be noted that that we employed the wavelength division multiplexing (WDM) technique to enable the multi-channel sensing capability [5].

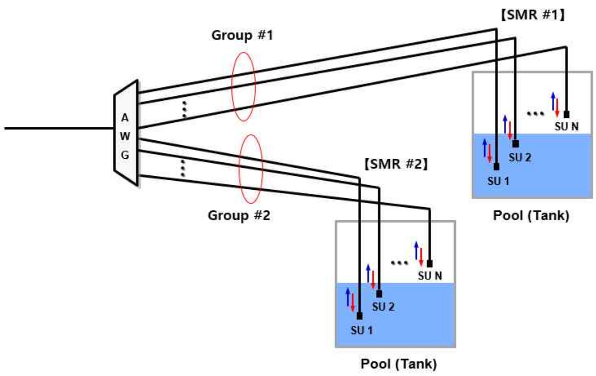

Fig. 3. Configuration of sensing units according to the assigned groups for water level measurement

3. Measurement Result

As stated earlier, the water level measurement system exploits the WDM technique to provide the multi-channel sensing characteristic. We demonstrated the proposed method without considering the transmission length. The experimental setup includes the C-band (1530~1565 nm) BLS that generates ASE light. The employed AWG provides 8 WDM channels (i.e., ch 1~ 8) with bandwidth shape of flat-top type. Its channel spacing and 3-dB bandwidth are 1.6 nm and 1.03 nm, respectively. For demonstration, 4 out of the 8 SUs were assigned to Group 1 (Ch 1~4), while the remaining 4 were assigned to Group 2 (Ch 5~8). The 4 SUs placed in the pool allow the measurement of 5 discrete water levels.

Fig. 4 presents the measurement results of the optical spectra for the four SUs in Group #1 at (a) the lowest, (b) intermediate, and (c) full water levels, respectively. The peak power difference between SU in the air and in the water was more than 10 dB. Thus, by detecting the reflected optical power from the SUs, the water level can be monitored easily.

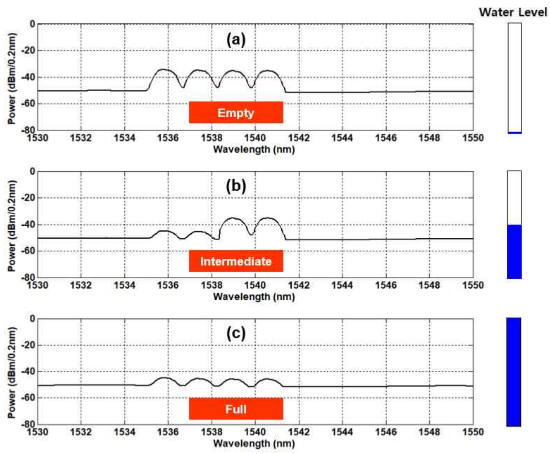

Fig. 4. Measured optical spectra of group #1 (a) the lowest water level (b) 1/2 water level (c) full water level

Next, we simultaneously measured the optical spectra reflected from the 4 SUs installed in each of the two groups. As shown in Fig. 5, the corresponding spectra were measured according to the water level in each water pool.

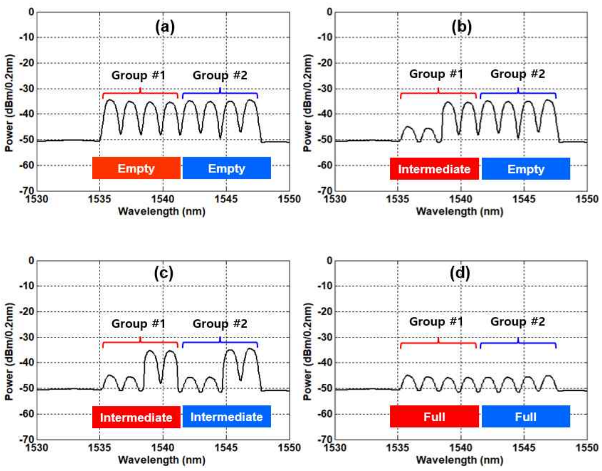

Fig. 5. Measured optical spectra of group #1 and group #2 (a) the lowest -the lowest water level (b) half -the lowest water level (c) half-half water level (d) full-full water level

4. Conclusions

This paper presents an alternative measurement system based on the optical fiber sensors to simultaneously monitor essential parameters (such as water level) for multi-unit SMRs. Especially, we investigated the feasibility of water level measurement by utilizing the wavelength division multiplexing technique. The multi-channel sensing capability, separated by groups, was successfully demonstrated with 8 AWG channels (i.e., 4 SUs x 2 Groups).

Due to its simple architecture and passive characteristic, it is possible to provide an emergency response solution to acquire reliable safety information for multi-unit SMRs. It should be noted that the spatial resolution of water level or the maximum number of accommodated groups can be easily increased by utilizing another wavelength band of BLS with a cyclic characteristic of AWG [6] and/or reducing the channel bandwidth of AWG [7].

ACKNOWLEDGEMEMT

This work was supported by the Nuclear Safety Research Program through the Regulatory Research Management Agency for SMRS (RMAS) and the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 1500-1501-409).

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