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Study on Water Level Measurement Method for Application of Small Modular Reactor

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1. Introduction

Recently, small modular reactors (SMRs) are being developed in many countries to address the increasing energy demand. With micro grids, SMR units can provide highly reliable and secure electric power including non-electrical applications such as district heating, desalination, hydrogen production, industrial process heat supply and so on [1]. SMR technologies aim for cost efficiency through modularization with shorter construction schedules than those of conventional nuclear power plants (NPPs) [2]. In 2020, the U.S. Nuclear Regulatory Commission (NRC) has approved the design certification of NuScale SMR which is based on i-PWR (integral pressurized water reactor) type [3]. Due to its compact size and design characteristics, it has been faced with new challenges for i-PWR SMR I&C systems such as measurement issues with reactor coolant system coolant levels during accident conditions. In the event of an accident in which all safety measures have failed to keep adequate coolant levels, other alternative level measurement methods can be used such as ultrasonic technologies or sensor thermal response [1].

In this paper, we also present other alternative coolant (i.e., water) level measurement method based on optical fiber sensor (OFS) during an accident.

2. Advanced Water Level Measurement Method

2.1 Principle of Water Level Measurement with Optical Fiber Sensor

The basic principle for water level measurement is based on the Fresnel reflection at the end facet of OFS (i.e., sensing unit). The sensing unit (SU) is a commercial fiber optic patch-cord including standard SC/PC type connectors. The change in the surrounding medium (i.e., refractive index) of SU induces the change of reflected optical power, where the 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 or 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. Then, the calculated Fresnel reflection coefficients in the air (R_{air}) and water (R_{water}) are 0.0336 and 0.0024, respectively. The reflected (peak) power difference between at the air and water is about 11.6 dB without consideration of the background noise power.

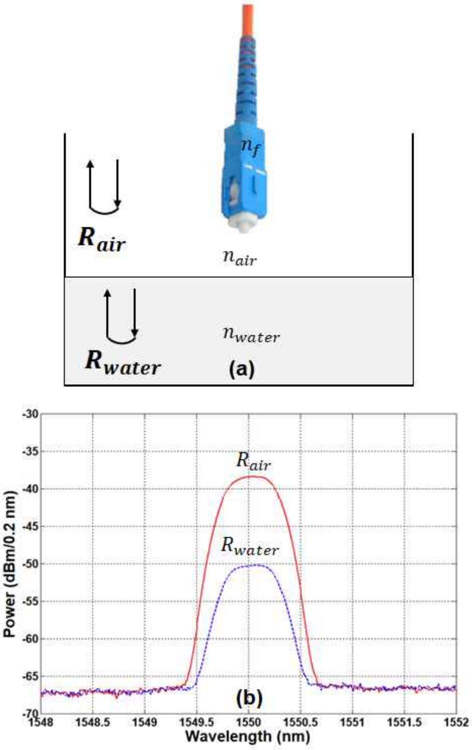

Fig. 1. (a) Schematic drawing of measurement principle (b) measured optical spectra with Fresnel reflection

Fig. 1 (a) shows a picture of the SU, which is based on a single mode fiber (SMF) including the standard SC/PC type connectors with a ceramic ferrule diameter of 2.5 mm at the ends of the fiber. As mentioned above, the reflection power is changed according to the refractive index of materials (i.e., R_{air} or R_{water}). These measured optical spectra are shown in Fig. 1 (b).

2.2 Application on Small Modular Reactor for Water Level Measurement

Fig. 2 shows the architecture of optical fiber sensor system for water level measurement. This system can be divided into four functional components:

- Reflectometer: It is located at the MCR as a monitoring station for emergency response. The reflectometer comprises a Broadband Light Source (BLS) for seeding Amplified Spontaneous Emission (ASE) light to the optical fiber sensors, 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.
- SMF: it is employed as a transmission media where its length would be extended to a few kilometers.
- AWG: an Arrayed Waveguide Grating (AWG) plays an important role of for multiplexing/demultiplexing the ASE lights for multiple optical fiber sensors.
- SU: Those SUs are installed vertically in the pool where each unit represents a specific water level.

Noting that we employed the wavelength division multiplexing (WDM) technique to enable the multi-channel sensing capability with using a C-band BLS (based on ASE) as a seed light and an AWG for channel multiplexing/de-multiplexing [5].

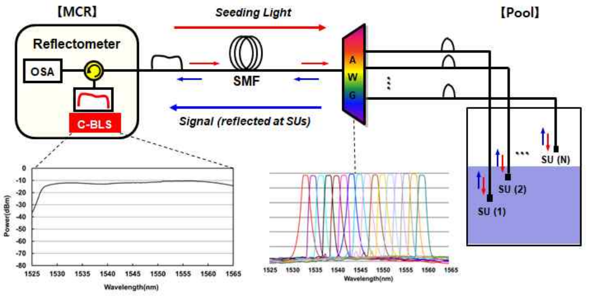

Fig. 2. Architecture of water level measurement system.

The optical signal path for level sensing is as follows. First, the C-band BLS at the MCR is delivered towards the AWG via the optical circulator and the SMF. Then, the transmitted BLS is spectrum-sliced by the AWG according to the dedicated channel wavelengths. The spectrum-sliced ASE lights are delivered to the SUs which is installed inside of SMR vertically. At the end of each SU, a small portion of the light is back-reflected towards the MCR, where the reflectance depends on whether each SU is in the air or in the water. The reflected light is multiplexed by the AWG and sent back to the MCR via the SMF. Finally, the OSA measures the spectrum of optical signal that contains the water level information in real-time basis.

3. Measurement Result with Optical Fiber Sensor

As mentioned above, the water level measurement method exploits the WDM technique to provide the multi-channel sensing characteristic. We demonstrated the proposed method at the back-to-back condition without considering the transmission length. The experimental setup includes the C-band (1530~1565 nm) BLS that generates ASE light. The total spectral width and flatness of its BLS are approximately 32 nm and 1.5 dB, respectively. The employed AWG provides 16 WDM channels with bandwidth shape of flat-top type. In this demonstration, we just utilized 7 channels of AWG for water level measurement. Its channel spacing and 3-dB bandwidth are 1.6 nm and 1.03 nm, respectively. The 7 SUs were placed in the pool, and it allows the measuring of 8 discrete water levels. Fig. 3 shows the measurement result of the optical spectra at the (a) lowest (b) full water level, respectively. The peak power difference between SU in the air and in the water is approximately 11.6 dB regardless of the channel wavelength. It implies that this measured parameter can be selected as an indicator for the water level monitoring during an accident due to its inherent passive characteristic.

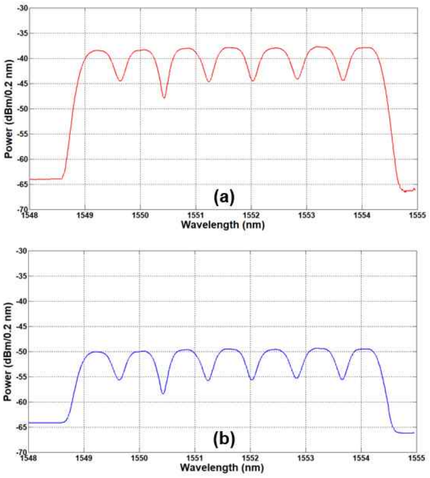

Fig. 3. Measured optical spectra (a) the lowest water level (b) full water level

4. Conclusions

This paper presents an alternative coolant (i.e., water) level measurement method for SMR application during an accident. Especially, we investigated the feasibility of water level measurement based on optical fiber sensors by utilizing the wavelength division multiplexing technique. For this, the multi-channel sensing capability was demonstrated with 7 AWG channels (i.e., SU). Due to its simple architecture and passive characteristic, it is possible to provide an emergency response solution to acquire reliable safety information. Noting that those SUs may be installed inside of the vessel that provides the harsh environment such as high temperature and high radiation. However, it is expected to mitigate these installation costraints with optical fiber sensors due to its robust characteristic against external environments (electromagnetic interference, radiation, etc.) [6, 7]. This measurement method needs to be further investigated, in terms of evaluation and qualification for SMR.

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