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Development of a portable heavy-water leak sensor based on laser absorption spectroscopy

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ABSTRACT

A compact and portable leak sensor based on cavity enhanced absorption spectroscopy has been newly developed for a detection of heavy water leakage which may happen in the facilities using heavy water such as pressurized heavy water reactor (PHWR). The developed portable sensor is suitable as an individual instrument for the measuring leak rate and finding the leak location because it is sufficiently compact in size and weight and operated by using an internal battery. In the performance test, the minimum detectable leak rate was estimated as 0.05 g/day from the calibration curve. This new sensor is expected to be a reliable and promising device for the detection of heavy water leakage since it has advantages on real-time monitoring and early detection for nuclear safety.

1. Introduction

Heavy water (D_2O) is used as a neutron moderator and coolant in a pressurized heavy water reactor (PHWR). Although many improved technologies for safety have been developed and implemented in those facilities, the possible risk of heavy water leakages still exists. Since the leaked heavy water contains tritium (^3H), the heavy water leaks can cause the release of the radioactive tritium into the environment as well as sudden shutdowns of the facilities. Actually, many leakage events have been reported at the PHWR plants and research reactors all over the world. For these reasons, the facilities using heavy water strongly requires a reliable system to continuously monitor heavy water leaks during normal operation of reactors (King, 2005; U.S. Nuclear Regulatory Commission, 2007).

Currently, the PHWR plants uses a tritium detection method for heavy water leaks because leaked heavy water contains tritium, which is produced by the neutron activation of deuterium. There are two conventional tritium detection methods. One is Liquid Scintillation Counter (LSC) and the other is Fixed Tritium Air Monitor (FTAM). However, those two methods have some drawbacks. In case of LSC, they collect air samples over several hours in many rooms and measure the tritium concentration every 4–8 h. So, it is difficult to detect leaks in real time and also impossible to find the exact leak locations. For real time monitoring, they are using FTAM which contains an ion chamber. However, this method lacks of both sensitivity and linearity, and it has some limitation to detect a low rated leak and find the exact leak location. Conventional methods are less effective in PHWR with Tritium Removal facility (TRF) because these conventional methods basically detect radioactive tritium instead of leaked heavy water.

As a specific method for the detection of heavy water, Fourier Transform infrared (FT-IR) spectroscopy is used. Although the FT-IR spectroscopy is a good analytical method to measure heavy water without using any chemical reagents, the sensitivity is not enough to detect a low-rated leak.

In order to overcome the limitation of the conventional techniques, we have recently developed a laser-based heavy water leak sensor (Lee et al., 2012). Our portable sensor is based on the OA-ICOS technique. It is one of the advanced techniques of cavity enhanced absorption spectroscopy (CEAS). It is considered to be a simple and robust spectroscopic tool because it doesn't need additional complex setup for cavity length modulation or stabilization. Moreover, it is less susceptible to vibrations or perturbations compared to other long-path techniques because it is less sensitive to the beam alignment.

Using this sensor, leak events could be monitored by detecting a small change in semi-heavy water (HDO) concentration induced by the exchange reaction of leaked heavy water (D_2O) with light

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water (H_2O). From the feasibility test, we found out that the sensor has an outstanding capability in terms of sensitivity for detecting a very low rated leak from reactor components and in its ability to find exact leak locations.

However, the developed apparatus has some limitations caused by its weight and size. It should be placed at a fixed location of the PHWR plant because the movement of the detector was not easy (but possible). The collected air sample was sent to the laser leak detector by using a long hose up to 100 m and analyzed for detecting heavy water leaks. In this case, if the distance between the detector and the sampling position becomes longer, the sample transit time through a hose also becomes longer and, consequently, a time delay about 1 min occurred to determine whether the leak is or not. Moreover, it has had some constraints to find leaks occurring at pipelines and pumps located some narrow spaces. In view of these points, a smaller equipment as portable for individual use would enable a plant personnel to find leaks at the pipes, valves, and pumps more conveniently.

In this paper, we reported about the more advanced leak monitoring device as a portable sensor for individual use in the facilities using heavy water. For the portability, we decreased its size and weight by improving the laser absorption cell, adopting a compact data analysis system, and using a miniature vacuum pump and internal battery. Finally, the developed portable device was assembled to be used as backpack type for individual use. Also, the sensitivity of the new device should be satisfied with the needed minimum sensitivity proposed by the general CANDU operational guidelines, 1 gallon per minute.

After the feasibility test, we presume that this new portable sensor is expected to be a reliable and promising device for the detection of heavy water leakage since it has some advantages on real-time monitoring and early detection for nuclear safety.

2. Sensor description

The assembled sensor was made easy to carry. The weight of the sensor is only 6.1 kg, the total weight including control PC, sampling probe, and the replacement battery is less than 8 kg. It is wearable and also easy to use to search for the leak point as shown in Fig. 1.

A simplified architecture of the developed portable leak sensor is given in Fig. 2. It contains an optical module which consists with a laser diode as a light source, an optical cavity and a photodetector with a lens array. An air inlet and an outlet port were provided for the sample gas flow at the side of the absorption cell. A vacuum pump for the sample gas flow is attached to the module, and the other units such as an oscilloscope, function generator and power supply are included in an aluminum box. Finally the box is packed in a backpack. After wearing the backpack, an air sampling tube and a control PC can be coupled through the port ① and port ③, respectively.

A single-longitudinal-mode tunable distributed feedback (DFB) laser diode was used as a light source. By adjusting the temperature and driving the current of the laser diode, the wavelength could be tuned to near 1390 nm where several absorption peaks of H_2O and HDO molecules exist. The driving current was directly controlled and modulated by an external function generator via an LD driver ④ (Thorlabs, CLD1015). In order for the sensor to be a portable device, the LD driver was selected by considering its size and the LD was installed in this driver.

The DFB laser beam was sent to an absorption cell through a single mode fiber. Before the beam was inserted into the absorption cell, it was collimated using a fiberport containing an aspheric antireflection-coated lens. The fiberport ⑤ (Thorlabs, PAF-X-5-C) allowed an aspheric lens element to be micro-positioned with respect to the fixed position of the fiber tip, which enabled the lens to be linearly translated along all three axes and enabled the pitch and yaw of the lens to be adjusted. With the help of the fiberport, the incident angle and the divergence of the laser beam was conveniently adjusted for the appropriate alignment in the cell. We found that the slightly focused beam was good for minimizing the interference noise which might occur by the overlapping of the reflected beams and enhanced by the characteristics of the cavity.

A vacuum-tight acetal (engineering plastic) absorption cell ⑥ was designed for a sensitive laser spectroscopy. The cavity enhanced absorption spectroscopy (CEAS) technique was adopted in our devices. It was designed as an optical cavity which was consisted of a 91 mm long tube and two highly reflective ($R = 0.9995$ at 1390 nm) plano-concave mirrors with 1 inch diameter. In the cavity, the light absorption by water molecules is enhanced by the lengthened absorption path due to the successive reflections between mirrors.

The laser beam was aligned to be incident on the first mirror surface at a distance from the center of the mirror and it was also tilted with an angle with respect to the cavity axis. The optimized incident position and angle can be evaluated geometrically by using the results from Harriott Cell (Herriot et al., 1964). In this condition, the reflections on the mirror formed a circled spot pattern and the neighboring spots were separated with an angle. Then, the light becomes re-entrant after several round trips. As

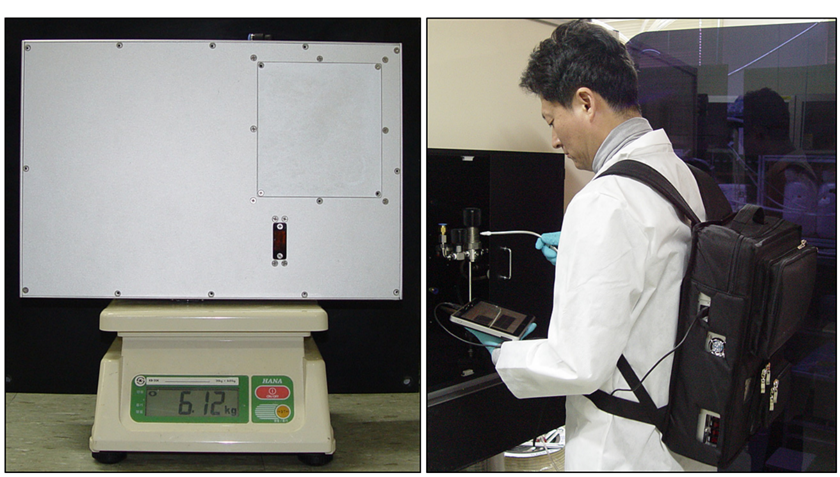

Fig. 1. The developed portable leak sensor body (left) and picture of searching for the leak point with the sensor (right).