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Liquid level sensing for harsh environment applications using distributed fiber optic temperature measurements☆

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ABSTRACT

This work demonstrates the measurement of liquid level from spatially distributed temperature measurements using optical frequency domain reflectometry. The goal of this work is to provide initial evidence for a liquid level sensor concept that could be applied in harsh environments such as those with: conductive, flammable, or other chemically aggressive media; electromagnetic interference; high temperatures (up to ~1000 °C); and neutron/gamma radiation. The sensor concept includes fiber optic sensors, along with an insulated heater wire assembled inside a protective Inconel 600 sheath. When the heater is not powered, the sensor provides spatially distributed temperature measurements along the length of the fiber. When the heater is powered, the difference in heat transfer in the liquid vs. vapor sections leads to a higher fiber temperature at locations above the liquid/vapor interface. The initial demonstration described in this work tested the sensor in a tank of water that was drained in increments of 2.5 cm. A model for determining liquid level from the distributed temperature measurements was developed that resulted in an accuracy of ±0.5 cm. The paper addresses potential effects of axial conduction through the sensor sheath, as well as ways to limit these effects to avoid "smearing" of what would otherwise be a step change in temperature at the liquid/vapor interface.

1. Introduction

Following the Three Mile Island (TMI) nuclear accident, an expert panel reviewed candidate nuclear reactor liquid level sensors that could be implemented to improve operators' understanding of the core state, particularly during accident scenarios [1]. Liquid level in boiling water reactor (BWR) cores and in the pressurizer of a pressurized water reactor (PWR) is typically monitored using differential pressure sensors that utilize the relationship between the hydrostatic head and liquid level [2]. This simple technique is well known and has a long track record of success. However, the differential pressure due to the liquid level is often small (~9%) compared to the coolant pressure drop across the core during normal operation, which reduces the signal-to-noise ratio of the measurement. The measurement is therefore sensitive to changes in level, as well as changes in coolant pressure drop. Uncertainty in the measurement can also be introduced from temperature gradients in the connecting lines between the reactor vessel and the pressure transducers, or from flashing in the connecting lines during a core depressurization. Furthermore, pressure transients during a loss of coolant accident can damage the pressure transducers. None of the differential pressure sensors on the TMI-2 pressurizer survived the TMI nuclear accident. Development of accident-tolerant sensors that could potentially provide information to prevent a nuclear accident would complement the development of accident-tolerant fuels and fuel cladding [3] to ultimately improve reactor safety. Other applications for advanced liquid level sensors include steam generators in PWRs, advanced salt-cooled or liquid metal-cooled reactors, and non-nuclear applications such as those used in the petrochemical industry.

The expert panel for BWR liquid level sensors determined that a heated thermocouple sensor was the most promising candidate for measuring liquid level [1]. The noted disadvantages of this sensor include: (1) it can only measure liquid level at discrete points, (2) film condensation and run-off may occur, and (3) transient behavior may occur due to radiation-induced noise in the sensor cables. For environments such as a BWR operating under saturation conditions, it is somewhat difficult for any sensor to define the liquid level, because the void fraction is gradually changing along the

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length of the channel. The sensor developed in this effort is like a heated thermocouple sensor, except the thermocouple is replaced with a distributed fiber optic temperature sensor. This modification eliminates the concern regarding the discrete nature of the heated thermocouple sensor, as the proposed sensor provides a distributed temperature (and thus level) measurement. Also, since the measurement relies only on a difference in temperature at the liquid/vapor interface, signal drift is a much smaller concern, if the drift affects the temperature measurement equally for the liquid and vapor over the sensing range of interest.

Previous work has used various fiber optic–based techniques to measure liquid level because of their high accuracy, small size, and performance in high-temperature, chemically harsh environments. For nuclear applications, fiber optics and fiber-based sensors have been shown to degrade under irradiation and at high temperatures [4–9], but transmission and signal degradation may be tolerable, if the appropriate material (pure or F-doped silica), wavelength (near infrared), temperature, and measurement technique (non-intensity–based) are selected. Some techniques for measuring liquid level rely on total internal reflection of light at the interface between the end of a fiber (or a prism coupled to the fiber) and the liquid [10–13]. The intensity of the reflected light will change depending on whether there is liquid or vapor at the end of the fiber. These methods are not particularly well-suited for nuclear applications because (1) they are intensity-based and would suffer from radiation-induced attenuation, (2) they require the silica fiber to be in direct contact with high temperature, high pressure water (or other high temperature, chemically aggressive liquids that may be present in non-nuclear applications), and (3) they offer only discrete measurements. Some proposed variations [14–17] offer continuous level sensing, and for some cases, they are not strictly based on intensity. However, these techniques still require direct fiber contact with the liquid. Radar-based techniques that offer high sensitivity over a wide range have been proposed [18,19], but they require optical line of sight with the liquid, and they are sensitive to contamination of the optics and windows. Previous work has used optical frequency domain reflectometry (OFDR)-based distributed temperature measurements to measure level without any heat input [20]. However, this method would not be suitable for applications where the liquid and vapor are essentially at the same temperature. A technique similar to the one described in this paper was used previously to measure distributed coolant flow [21].

This work uses the spatially distributed temperature sensing capabilities of fiber optic–based sensors interrogated using OFDR with a small insulated heater wire to enable a continuous liquid level sensor that does not require the fiber to have direct contact with the liquid. This makes the sensor very robust, which is particularly important for making measurements in the harsh environment of a nuclear reactor or in petrochemical applications. Pulsing the heater wire provides a radial heat flux which results in a temperature change at the sheath/liquid interface that is dependent on the convective heat transfer coefficient, or for quiescent applications, the density and specific heat capacity. The convective heat transfer coefficient and the density are significantly higher for liquids compared to vapor for engineered systems operating far from the critical point. Heating the wire will cause a significantly larger increase in temperature in the vapor region compared to the liquid region. The spatial temperature profile in the liquid and vapor regions can be measured with sub-cm resolution. In theory, the sensor described in this work should be applicable to environments requiring exposure to: conductive or flammable media, electromagnetic interference, high temperatures (up to ~1000 °C), neutron/gamma radiation, and chemically aggressive coolants. Future work will investigate sensor performance in some of these environments.

2. Sensor concept and experimental methodology

The proposed sensor uses the distributed temperature sensing capabilities of optical frequency domain reflectometry. This technique can be used to measure spectral shifts resulting from local thermal expansion of inscribed fiber Bragg gratings or from Rayleigh backscattering from random density fluctuations inherent to standard singlemode fiber [22]. This work uses standard singlemode fiber interrogated using a Luna optical backscatter reflectometer (OBR), model 4600. Details describing the methodology for performing distributed temperature sensing using an OBR can be found elsewhere [23,24]. Briefly, a tunable laser is coupled to an interferometer with a reference arm and a measurement arm, which includes the fiber under test. As the tunable laser sweeps over a range of wavelengths, two detectors measure the two orthogonal polarization states of light coming directly from the reference arm and light reflected backwards along the entire length of the measurement arm. A Fourier transform of the two detector signals allows for determination of the reflected signal amplitude as a function of the optical path length difference between the reference and measurement signals. These path length differences are related to the spatial positions from which the reflections occurred. Windowing of the intensity vs. position data allows for transformation of small segments of data back into the frequency domain. The reflected spectrum is a function of the random density fluctuations that occur over the windowed region. When the local temperature increases, the reflected spectrum shifts due to local expansion. This spectral shift is calibrated to a change in temperature. Varying the window position along the spatial region of interest allows for calculation of the spatially distributed temperature.

There is a tradeoff between the spatial resolution and temperature resolution of the measurement. For this work, the gauge length of the windowed region (i.e., the region over which the temperature is determined) was chosen to be 1 cm, and the window was translated in 0.5 cm increments. The tunable laser was swept over a wavelength range of 42.6 nm centered at 1566.8 nm. Previous work has shown that for a 1 cm gauge length and 42 nm scan range, the spectral shift resolution is 0.11 GHz [23]. Using the standard calibration for polyimide-coated singlemode fiber, of 0.8 °C per GHz spectral shift [25,26], gives a temperature resolution of 0.1 °C. Measurements were made every ~20 s, which was sufficient for this work. The measurement time can be reduced to below 1 s for applications with shorter transients.

To form a liquid level sensor, standard SMF-28 singlemode optical fibers were placed inside two of the four through-holes in a series of stacked ceramic insulators (Omega part FRX-164116) as shown in Fig. 1. As indicated in Fig. 1, the distance from the top of the tank to the liquid level is defined as z. The insulators are nominally 1.6 mm outer diameter × 15.2 cm long with 0.4 mm diameter holes. A 0.25 mm diameter Nichrome heater wire was passed through one of the remaining holes from the top of the stack down to the bottom. The heater wire was then bent 180° and passed back up to the top of the stack through the last remaining hole. The entire assembly was inserted inside an Inconel 600 sheath (3.2 mm outer diameter × 0.32 mm thick). For the proof-of-principle experiment described in this work, an additional 0.5 mm diameter Nichrome wire was placed inside the sheath to take up space. This was necessary to keep the stack of insulators aligned inside the relatively large space between the insulator's outer diameter and the sheath's inner diameter. While standard-size components were used in this work for convenience, a tighter fit would be required for future experiments to prevent the need for any additional wire.

To measure liquid level, the spatially distributed temperature is measured before and after applying a small electrical voltage across the leads of the heater wire. This drives a small heat flux at the outer surface of the sheath. For flowing coolant applications