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Integrated microfluidic-based sensor module for real-time measurement of temperature, conductivity, and salinity to monitor reverse osmosis

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HIGHLIGHTS

- We fabricated a microfluidic sensor module for monitoring reverse osmosis.
- It can measure temperature, conductivity, and salinity.
- It can reduce sensor manufacturing costs and operating costs for monitoring.
- Product water is effectively monitored using the module.
- The measurement error relative to a reference sensor was less than 8% over five days.

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ABSTRACT

This paper proposes an integrated microfluidic-based sensor module for real-time monitoring of reverse osmosis (RO) that measures temperature, conductivity, and salinity. Current methods suffer from high operating costs because of the amount of instrumentation required and the labor involved in taking real-time readings at each step of the RO process. This sensor module allows for lower manufacturing costs and lower operating costs for the RO process, because it makes remote monitoring of the process at the base station possible. The microfluidic device is constructed from a thin metal film and a microfluidic channel that was fabricated using the microelectromechanical system (MEMS) technology, and it can simultaneously measure both temperature and conductivity. It includes a power board for the generation of an AC voltage signal and DC power from a 9 V battery, a sensing board for microfluidic-based measurement, and a mote for wireless communication. To verify the effectiveness of the sensor module, we used it to monitor the product water harvested from a seawater desalination plant over a five-day period. The encouraging results indicate that the proposed sensor module could be used to monitor industrial RO processes in the near future.

1. Introduction

Desalination has gained global prominence as a potential method for alleviating drinking water shortages [1,2]. There are many desalination methods including the multistage flash (MSF), multieffect distillation (MED), reverse osmosis (RO), and nanofiltration (NF) techniques. Among the different techniques available, seawater reverse osmosis (SWRO) is popular because it is simple and efficient and, under optimal conditions, can reduce operating costs [2,3]. It has been reported that membrane-based desalination accounts for approximately 44% of water desalination conducted across the world [4,5].

The SWRO process comprises many steps including seawater intake, pretreatment of raw seawater, RO with a semipermeable membrane, and rejection of concentrated seawater. The RO process is affected by many factors including pressure, concentration polarization, fouling, scaling, water quality, and temperature [2,6–10]. Fouling of RO membranes severely affects their efficiency and is a major concern in the desalination industry [5]. To monitor the desalination process and to avoid these problems, several parameters including pressure, flow, conductivity, pH, oxidation–reduction potential (ORP), temperature, salinity, and silt density index (SDI) are measured regularly with on-stream or benchtop instruments [3,4]. Conductivity in particular is an important monitoring parameter because it indicates the concentration of dissolved salts in the water [4].

Many kinds of commercial on-stream or benchtop instruments are available for measuring these parameters. However, they often need to be installed at multiple monitoring points along the RO production

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line to effectively monitor the process, and the measured information often must be read manually. A small microfluidic-based sensor module for measuring water quality is capable of decreasing the production costs for these sensors, given that they can be mass produced using the microelectromechanical system (MEMS) technology. In addition, microfluidics involves the use of only a small sample volume and requires only a short measurement time [11].

MEMS-based microfluidic devices have recently been used in several environmental monitoring applications. Various integrated sensors have been developed, including a liquid crystalline polymer (LCP)-based conductivity cell, a resistive temperature sensor, and a piezoelectric pressure sensor for depth measurement [12]. Sensor packaging methods using polystyrene tubes and epoxy have also been developed to allow water quality measurement in harsh environments [13].

In this research, we developed a microfluidic-based integrated sensor module for the continuous measurement of conductivity, temperature, and salinity. In addition, the sensor contains a wireless communication module for transferring water quality data to the base station and thus eliminates the need for daily manual measurements. In this way, the sensor reduces the manufacturing, monitoring, and maintenance costs associated with the RO process.

2. Module design and development

2.1. Integrated microfluidic-based sensor module

Fig. 1 shows the integrated microfluidic-based sensor module, which is composed of three layers. The power board generates an AC voltage signal that drives a conductivity sensor and DC signals that supply power to the op-amp, analog-to-digital convertor (ADC), and a Zigbee-based [14] wireless sensor communication mote module (CC2430, Chipcon, Texas Instruments, Texas, US). The power board uses a 9 V battery, which eliminates the need for a power supply. The sensor board measures temperature and conductivity, regulates the measured analog signals, and converts analog signals to digital signals. The board contains integrated microfluidic devices with sizes of 25 mm and 15 mm. The temperature sensor is connected to the board by direct contact, and the conductivity sensor uses gold wiring. Broken sensor boards can be replaced easily. The communication module is based on the CC2430 System-on-Chip (SoC), which acquires sensor data through input peripherals and delivers those sensor data to the base station. It also performs power management for the sensor module in order to reduce power consumption during idle periods when no measurements are being performed.

Fig. 2 shows a microscopic view of the integrated microfluidic device. The temperature and conductivity sensors are placed on the glass substrate, and the water sample flows through a microfluidic channel with a width of 500 μm and a height of 75 μm. The thermocouple-based temperature sensor is made of a copper (Cu) electrode and a constantan ($Cu^{55\%}$–$Ni^{45\%}$ alloy) electrode. The widths of the Cu electrode and the Cu–Ni electrode are 1000 μm and 700 μm, respectively, and the junction between them measures 500 μm. The junction is located within the microfluidic channel.

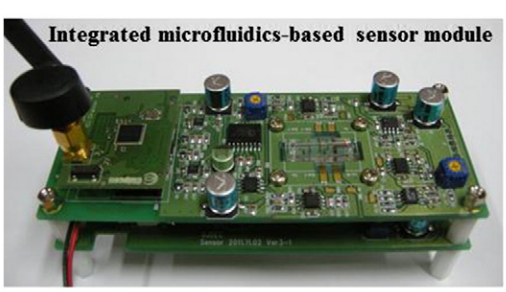
The conductivity sensor uses four gold (Au) electrodes: one to inject the AC voltage signal (V_{in}, 1st), one for grounding (GND, 4th), and two for measuring the potential drop (ΔV, 2nd and 3rd). The widths of the 1st and 4th electrodes are 500 μm, and the widths of the 2nd and 3rd electrodes are 50 μm. The gap between the 1st and 4th electrodes is 800 μm, and the gap between the 2nd and 3rd electrodes is 600 μm. The AC voltage signal from the power board is injected into the first electrode, and the injected current cannot flow into the 2nd and 3rd electrodes because they are directly connected to an op-amp that has a high load impedance. Therefore, the electrodes correctly measure the potential drop.

2.2. Design of the microfluidic device

2.2.1. Temperature sensor

The generation of a thermoelectric voltage due to a temperature difference between two different metals is known as the Seebeck effect, and the associated proportional constant is called the Seebeck coefficient. Thermocouples taking advantage of this effect are widely used for temperature measurements and can also be used to change a temperature gradient into a voltage. They are inexpensive and can measure a wide range of temperatures. Unlike conventional rod-type thermocouples, microscale thin-film thermocouples have a high spatial resolution and can be fabricated easily on glass materials. They are almost as sensitive as conventional thermocouples [15]. A T-type thermocouple (Cu and Cu–Ni) is used in this experiment.

Fig. 3 shows a schematic of the temperature measurement system using the thin-film thermocouple. On the printed circuit board (PCB), Cu and Cu–Ni are connected to the gold (Au) line. The temperature measurement unit includes a cold-junction compensator and an op-amp to amplify the measured temperature signal (Fig. 3(b)). There are five junction temperatures: T_f, T_{r1}, T_{r2}, T_{j1}, and T_{j2}. T_f and T_j denote the temperatures at the junctions between Cu and Cu–Ni and between Au and the temperature measurement unit, respectively. T_{r1} and T_{r2} denote the temperatures at the junctions between Au and Cu and between Au and Cu–Ni, respectively. In a conventional thermocouple, the thermoelectric voltage indicates the temperature difference between the measurement junction and the reference junction. To obtain the absolute temperature,



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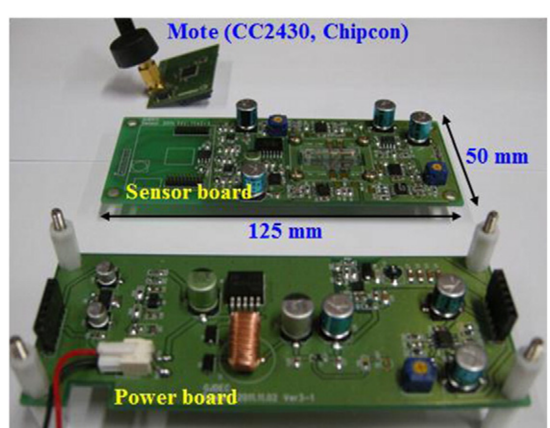

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Fig. 1. Photographs of (a) the integrated microfluidic-based sensor module and (b) the components of the module. The module is composed of three layers: the power board for generating AC voltage signals, the sensor board for measuring temperature and conductivity, and the mote for transferring measured signals to the base station.