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Temperature distribution monitoring of a coiled flow channel in microwave heating using an optical fiber sensing technique

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ABSTRACT

We demonstrate the temperature distribution monitoring of a coiled flow channel in a microwave reactor that was designed for microwave-assisted continuous-flow synthesis. The monitoring is conducted using an optical fiber sensing technique, which can monitor the temperature distribution along the coiled flow channel. The sensing system successfully observed the inhomogeneous nature of the microwave heating, and the effect of water flow on the temperature distribution. We discuss the cause of the inhomogeneous heating by comparing the observed temperature distributions and the electric fields inside the reactor, as calculated by numerical simulations.

1. Introduction

Microwave heating techniques are being widely used as synthesis assists [1,2]. One of the major reasons for this is that microwave heating can dramatically reduce reaction times. Compared with conventional synthesis assists such as oil bath heating, microwave heating can reduce reaction times from days and hours to minutes and seconds [3]. To fully utilize this advantage, active research and development is being conducted on microwave-assisted continuous-flow synthesis techniques [4,5].

It is important to observe and understand the microwave heating process to ensure the effective design and operation of continuous-flow microwave reactors. Various approaches are used to observe the microwave heating process, especially by monitoring the temperature of the reaction mixtures. Optical fiber sensors possess promising characteristics that can be leveraged for this purpose. Optical fibers are typically small in size, passive, resistant to harsh environments and immune to electromagnetic interference [6]. There have been various reports describing successful temperature monitoring using optical fiber sensors in electromagnetic environments [2,7–9]. It was claimed in some works that the temperatures measured at multiple points inside reaction vessels were non-uniform [2,7,10]. This implies that the relationship between the heating parameters, such as the input power used for the microwaves, and the synthesis results is not straightforward without having prior knowledge of the inhomogeneous temperature distribution. Therefore, accurate monitoring of the inhomogeneous temperature distribution is a key issue.

One of the major challenges in monitoring the inhomogeneous temperature distributions associated with microwave heating is the number of measurement points. It is difficult to collect sufficient data using electromagnetically immune optical fiber probes, especially in continuous-flow reactors, where the inhomogeneous temperature distribution is expected to expand over the length of the flow channel. Non-contact measurement methods such as infrared (IR) radiometry can monitor the distributions of the temperature at the surface of the reaction channels. However, it is not always correct to assume that the surface temperature directly corresponds to the temperature of the reaction mixtures [2,7–9].

Several optical fiber distributed sensing techniques have been developed, such as optical time domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR), which enable monitoring of the temperature distributions along the fiber. OFDR in particular possesses a high spatial resolution (on the order of mm), which is expected to provide abundant data to permit the

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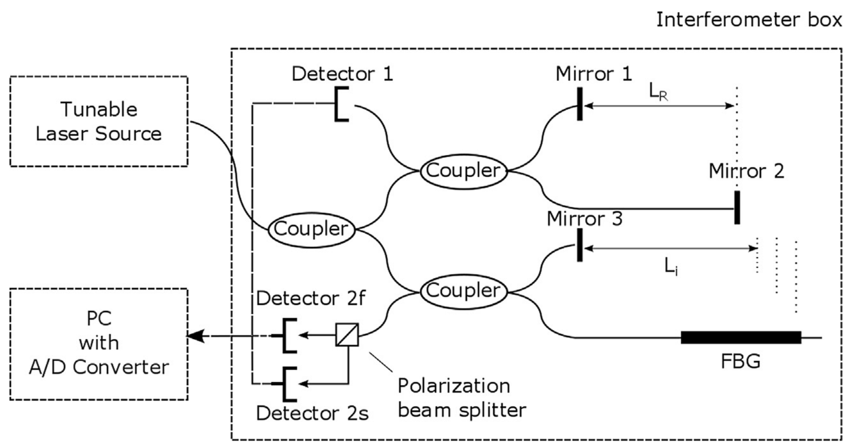

Fig. 1. Schematic of the sensing system based on OFDR.

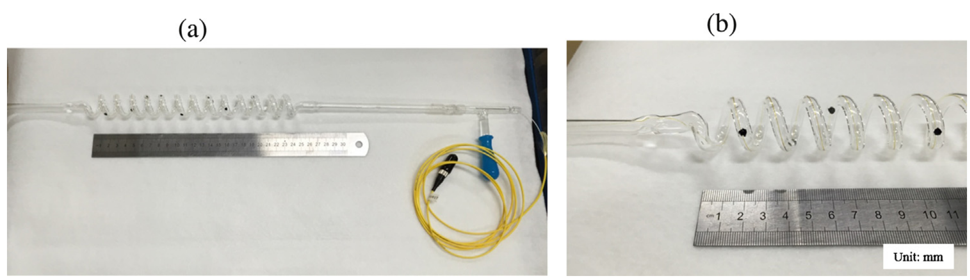

Fig. 2. Image of the coiled channel. (The black dots on the channel wall were marked for reference purposes). (a) Overall view (b) Enlarged view.

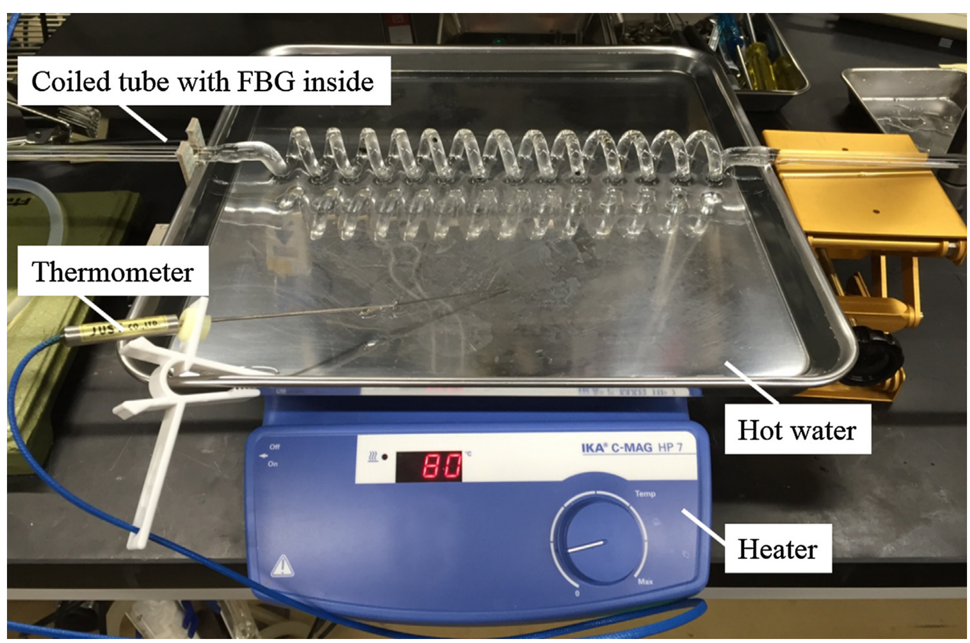

Fig. 3. Picture of the hot water bath.

visualization of the distributions of the temperature in the reaction mixture [11–14]. In a previous work, this technique effectively demonstrated the capability to monitor temperature distributions in a microwave oven [15]. In this paper, we applied an equivalent OFDR sensing system to monitor the temperature distributions in a coiled flow channel in a microwave reactor. The inhomogeneous nature of microwave heating for the coiled flow channel and the effect of the water flow are to be monitored. In addition, we discuss the causes of the inhomogeneous heating using electric fields simulations.

2. Experimental

2.1. Sensing system

We used a long-length fiber Bragg grating (FBG) with a sensing range of approximately 50 cm. This FBG was connected to the OFDR