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Distributed Fibre Optic Sensors for Solid-Liquid Phase Change Detection in Thermal Energy Storage Applications

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1. ABSTRACT

This paper presents a distributed optical fibre sensor for real-time detection of solid-liquid phase changes in thermal energy storage material (n-octadecane). The sensor probes, made by splicing a no-core fibre (NCF) between two single-mode fibres (SMFs), form a sensor array. Due to differing refractive indices (RI) of solid and liquid n-octadecane, the array exhibits a step-like output power change during phase transitions. Optical fibre sensors are crucial in phase change energy storage materials as they offer precise, real-time monitoring and can be integrated into various systems with minimal intrusion. Experimental results confirm the sensor's ability to monitor phase changes, highlighting its potential to enhance thermal energy storage systems and advance distributed optical fibre sensing technology.

2. INTRODUCTION

Phase change materials (PCMs) have been extensively studied for their applications in energy storage, thermal management, electronic cooling, and other engineering fields [1]. Their ability to absorb and release latent heat during solid-liquid transitions makes them ideal for thermal energy storage systems. However, accurately detecting and characterizing these phase changes remains challenging due to the complex heat and mass interactions during transitions, necessitating advanced sensing techniques with high spatial resolution and real-time data acquisition.

Fiber optic sensors, known for their simplicity, high sensitivity, cost-effectiveness, and immunity to electromagnetic interference, are widely used for measuring physical parameters such as temperature and strain. Numerous studies have explored their application in detecting phase changes. For example, Arnon et al. used a fiber-optic evanescent wave spectroscopic technique to detect phase changes in water by monitoring absorbance changes, but this method's complexity and reliance on special silver halide-based fibres pose challenges [2]. Mani et al. used a Fresnel reflection fiber sensor to monitor the crystallization of water and NaCl solutions, relying on changes in reflectivity associated with the material's refractive index (RI) during phase transitions [3]. However, these studies focus on single-point measurements, while multi-point measurements are essential for monitoring energy storage processes.

This paper proposes and experimentally demonstrates a distributed optical fiber sensor for detecting solid-liquid phase changes. The sensor probe, created by splicing a short section of no-core fibre (NCF) between two single-mode

*Corresponding Author: c.wang@kent.ac.uk fibres (SMFs), forms a distributed sensing system when two probes are connected in parallel. Phase change detection is achieved by monitoring optical power transmitted through the sensor array submerged in the sample. N-octadecane, chosen for its narrow temperature range of crystallization, repeatability, and transparency in the liquid phase, serves as the validation material. This characteristic allows direct observation of the phase change near the probe, validating the methodology.

3. METHDOLOGY

The proposed sensor system, shown in Fig. 1, features a 3 dB coupler connected to a 1550 nm wavelength laser. The coupler's outputs link to a distributed fibre sensor array comprising two sensors, with their outputs connected to optical power meters. The sensor probes, designed for immersion, consist of a no-core fiber segment spliced between two single-mode fiber sections, with the no-core fiber coatings removed. Temperature near the probes is monitored using K-type thermocouples. A Peltier element serves as the thermoelectric heating component.

N-octadecane is used as the sample. Previous research indicates that the refractive index (RI) of liquid n-octadecane is lower than that of the no-core fiber (NCF), while solid n-octadecane has a higher RI than the NCF. Thus, the sensor output is low when surrounded by solid n-octadecane and changes from low to high upon melting. Detecting this step-like output power change enables distributed solid-liquid phase change monitoring [4].

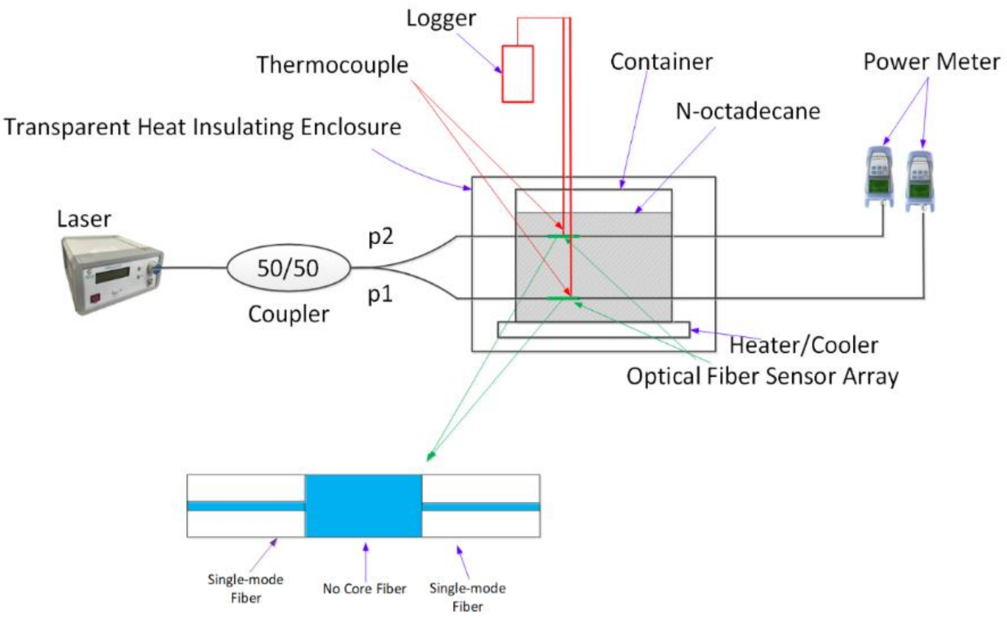

Fig. 1 Schematic diagram of the experimental setup.

4. RESULTS

To validate the proposed sensor, heating and cooling tests were conducted using a 5 ml sample of 99% pure n-octadecane, as depicted in Fig. 1. The fiber probes and thermocouples were immersed in the sample with a 2 mm gap between them and a 2 cm distance between sensor 1 and sensor 2. The thermocouples, connected to a logger, recorded the temperature near the fiber probes at 0.5 °C intervals.

Figure 2 illustrates the relationship between the output powers of the sensor probes and the temperature of n-octadecane during the heating cycle, based on data from the sensors and thermocouples. In the temperature range of 25.5 to 27.5 ℃, where n-octadecane is solid, sensor 1 records power levels from -20.2 dBm to -21.99 dBm, and sensor 2 records from -20.4 dBm to -22.5 dBm. In the 28 to 30 ℃ range, where n-octadecane is liquid, sensor 1's output ranges from -14.8 dBm to -14.3 dBm, while sensor 2's output ranges from -16.7 dBm to -16.4 dBm.

Both sensors show low output in the solid phase and higher output in the liquid phase, as expected. Monitoring these output levels allows tracking the phase change at different locations within the n-octadecane. Notably, both sensors experience output variations before and after the phase transition, likely due to strain and pressure on the fiber during n-octadecane melting.

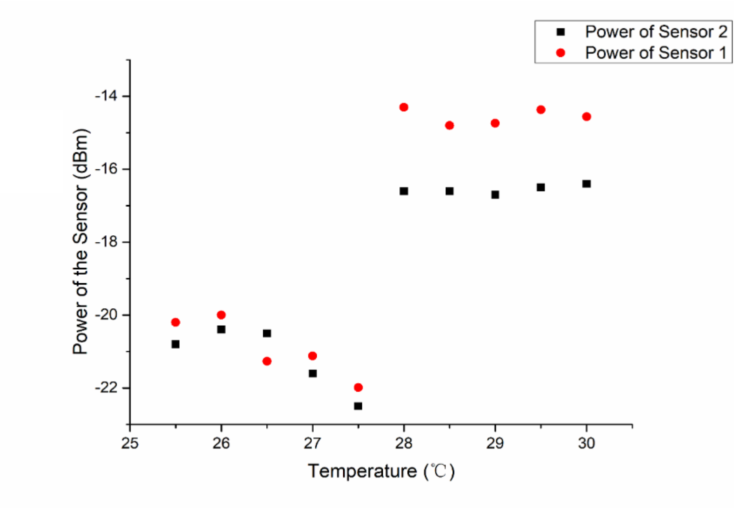

Fig. 2 Measurement results showing the optical power jump corresponding to phase change at two locations.

5. CONCLUSIONS

We propose and experimentally demonstrate a novel distributed optical fiber sensor based on a single-mode-no-core-single-mode fiber structure for detecting the phase state of n-octadecane. The experimental results show that both sensors exhibit low output when surrounded by solid n-octadecane and an abrupt increase when immersed in liquid n-octadecane. By monitoring the sensor output levels, the phase transition at different positions within the sample can be accurately detected.

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