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# Temperature monitoring using fibre optic sensors in a lead-bismuth eutectic cooled nuclear fuel assembly

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## HIGHLIGHTS

- We demonstrate the use of optical fibre sensors in lead-bismuth cooled installations.
- In this first of a kind experiment, we focus on temperature measurements of fuel rods
- We acquire the surface temperature with a resolution of 30 mK.
- We asses the condition of the installation during different steps of the operation.

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## ABSTRACT

In-core temperature measurements are crucial to assess the condition of nuclear reactor components. The sensors that measure temperature must respond adequately in order, for example, to actuate safety systems that will mitigate the consequences of an undesired temperature excursion and to prevent component failure. This issue is exacerbated in new reactor designs that use liquid metals, such as for example a molten lead-bismuth eutectic, as coolant. Unlike water cooled reactors that need to operate at high pressure to raise the boiling point of water, liquid metal cooled reactors can operate at high temperatures whilst keeping the pressure at lower levels. In this paper we demonstrate the use of optical fibre sensors to measure the temperature distribution in a lead-bismuth eutectic cooled installation and we derive functional input e.g. the temperature control system or other systems that rely on accurate temperature actuation. This first-of-a-kind experiment demonstrates the potential of optical fibre based instrumentation in these environments. We focus on measuring the surface temperature of the individual fuel rods in the fuel assembly, but the technique can also be applied to other components or sections of the installation. We show that these surface temperatures can be experimentally measured with limited intervention on the fuel pin owing to the small geometry and fundamental properties of the optical fibres. The unique properties of the fibre sensors allowed acquiring the surface temperatures with a resolution of 30 mK. With these sensors, we assess the condition of the test section containing the fuel assembly during different steps of the operation of the facility, including the heating and verification of the vacuum of the loop as well as the filling and draining of the LBE loop. We also identify a simulated electrical shut-down and heating circuit failure in the primed installation.

## 1. Introduction

This paper pertains to the research activities conducted with the aim to develop MYRRHA, which is a prototype nuclear reactor belonging to the so-called fourth generation (Aït Abderrahim et al., 2012). It is an accelerator driven reactor that is cooled by a molten lead-bismuth eutectic (LBE) at temperatures between 125 °C (i.e. the LBE melting temperature) and 400 °C. During operation, the reactor core outlet temperatures however are expected to reach 700 °C. As in any nuclear reactor, to ensure safe operation the temperature has to be monitored and controlled in every section or component (Hashemian, 2011). One particularly important section is the fuel assembly. In MYRRHA, one fuel assembly consists

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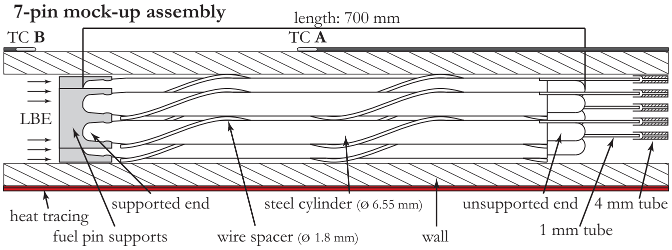

**Fig. 1.** Concept drawing of the fuel assembly.

of a total of 127 wire spaced parallel fuel rods. Fig. 1 illustrates a sub-assembly consisting of 7 fuel rods. These fuel rods are placed vertically in the reactor. The rods are mechanically fixed and supported at the bottom but not at the top. The LBE coolant is flowing upwards. A wire spacer is wrapped around every fuel rod to ensure that they remain properly spaced during operation. These wires limit the space between the individual fuel pins to a couple of millimetres. In order to have reliable temperature readings in the fuel assembly and use these readings in for example a control system, the sensor should not alter the flow of LBE. Therefore the sensor that is introduced in the fuel assembly needs to have very small dimensions.

Temperature measurements in opaque coolants are usually performed on the outer shell of the reactor or on the inside if there is sufficient space to adequately protect the sensors. Most often classical temperature sensors, such as thermocouples or resistance temperature detectors (RTDs), are used (Pettigrew, 2013; Lacanette, 2014). These types of sensors are susceptible to corrosive attacks and sensitive to various sources of error caused, for example, by electro-magnetic interference (see Lacanette, 2014). This may lead to measurement uncertainties when these sensors are located near sources of electromagnetic fields (Eckert and Gerbeth, 2002, 2008). Certain types of metals also suffer from embrittlement when exposed to LBE (Gong et al., 2014). This can limit the lifetime of classical temperature sensors. Furthermore the multitude of lead wires required to read out the sensors will fill the space between the fuel pins and consequently alter the coolant flow modifying the thermal conditions. An option to avoid such a problem is to scale the reactor core to equivalent set-ups in which for example water is used rather than molten metal coolants (e.g. Prakash et al., 2009; Someya et al., 2010). The scaling to water based set-ups is not always straightforward because all the fluid properties do not scale in the same manner. Measurements performed in a molten metal installation can therefore provide a more realistic insight in the temperature profiles inside the fuel bundle. Our goal was therefore to carry out temperature measurements in a flow of LBE at several locations on the surface of the individual fuel pins to investigate the temperature distribution along the fuel bundle in realistic conditions. These measurements can then be considered as valuable input to allow for adequate temperature control.

In order to measure the temperatures of the individual fuel pins as a function of time, we conducted experiments in a reactor mock-up containing half-scale fuel pins subjected to LBE flow conditions very close to the MYRRHA design. To achieve this goal, we instrumented each fuel pin in the mock-up with optical fibres containing several so called Bragg grating sensors. The use of these sensors for temperature measurements in nuclear reactors is already known for some time (Berghmans and Gusarov, 2011; Fernandez Fernandez et al., 2002; de Villiers et al., 2012), but they were never used as sensors in a flow of LBE. We show here that such optical fibre sensors are an adequate possibility to measure surface temperature on the fuel rods. Moreover, the properties of the optical sensors allow limiting the impact on the geometry of the fuel pins. This minimizes the influence of instrumentation on the coolant flow and thus on the thermal characteristics. We recall that the goal of the experiments was to evaluate the operation of the fibre sensors for temperature measurements in a mock-up LBE cooled loop and since no nuclear radiation is present, the effect of such radiation on the operation of the fibre sensors can be disregarded in the context of this paper. Note that the impact of various types of radiation on optical fibres and sensors made thereof has been extensively discussed in previous studies e.g. (Berghmans et al., 2008, 1996; Rego et al., 2005; Berghmans and Decréton, 1998; Gusarov et al., 1998).

The remainder of this paper is structured as follows. Section 2 describes the geometry of the experimental set-up and the LBE loop mock-up, as well as how the optical fibre sensors have been integrated. Section 3 deals with the experimental results and discusses how these relate to the operational modes of the loop. Section 4 closes our paper with a summary and conclusions.

## 2. Materials and measurement techniques

### 2.1. Experimental mock-up and fuel pin construction

We have constructed a LBE loop in order to expose a mock-up of a fuel assembly to a flow of LBE in conditions that mimic those anticipated in the MYRRHA reactor. Fig. 2 shows the full set-up, which measures 3.5 m by 2.5 m and which consists of a LBE reservoir, the actual test loop and the control systems. The loop can hold around 350 kg of LBE at temperatures up to 250 °C. A 5.5 kW motor (type FCA 132SA-2) powers the magnetically coupled three screw pump (type Krall K 55-118) to achieve mass flow rates up to 20.5 kg/s. The heating and control system (SCADA) relies on a network of pressure sensors, tachometers and 35 heating circuits each having several heat tracing lines combined k-type thermocouples mounted on the outer shell of the loop. We set the thermocouple sampling interval to 30 s. Prior to the start of the pump, the loop is heated and air is eliminated to prevent oxidation of the LBE. The loop is then filled with LBE and kept under argon flow at a slight overpressure (±1 bar extra) so as to avoid infiltration of oxygen.

The vertical test section, located shortly after the pump, consists of a 0.767 m long steel cylinder with a 51.2 mm inner diameter and equipped with a 0.450 m T-section on top. The T-section diverts the LBE flow and also functions as an egress point for the optical fibres.

The fuel pin mock-ups are made from stainless steel (316 L) cylindrical tubes with a diameter of 6.55 mm and a length of 700 mm (Fig. 1). The diameter corresponds to that of the actual rods that will be used in MYRRHA, whilst the length is only half of the actual value. The fuel pins are wrapped with a wire spacer (diameter 1.8 mm) in a helical fashion with a pitch of 265 mm. The fuel pin supports were secured in the test section using a flange connection. In MYRRHA, the fuel pins will be arranged in the fuel bundle in a hexagonal fashion and the vessel wall will tightly enclose the fuel bundle. To mimic the situation anticipated in MYRRHA, a hexagonal shell was placed around the fuel bundle.

### 2.2. Integration of fibre Bragg gratings

Due to the limited space of 1.8 mm between the individual fuel pins, optical fibre sensors are one of the very few options to measure temperature in the fuel assembly. In previous studies, we have already shown that these sensors are sufficiently sensitive to pick up the fuel pin vibration (De Pauw et al., 2013) and that their useful time in a LBE environment is sufficient to carry out meaningful measurements (Pauw et al., 2014; De Pauw et al., 2015). These studies focused on a particular type of fibre sensors called fibre Bragg gratings (FBGs).

A FBG consists of a periodic variation of the refractive index of the core of an optical fibre and is fabricated using dedicated