DISTRIBUTED TEMPERATURE SENSOR TESTING IN LIQUID SODIUM

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ABSTRACT

Rayleigh-backscatter-based distributed fiber optic sensors were immersed in sodium to obtain high-resolution liquid-sodium temperature measurements. Distributed temperature sensors (DTSs) functioned well up to 400 ˚C in a liquid sodium environment. The DTSs measured sodium column temperature and the temperature of a complex geometrical pattern that leveraged the flexibility of fiber optics. A single Ø 360 µm OD sensor registered dozens of temperatures along a length of over one meter at 100 Hz. We also demonstrated the capability to use a single DTS to simultaneously detect interfaces (e.g. sodium level) and measure temperature.

KEYWORDS
Distributed Temperature Sensor Liquid Metal

1. INTRODUCTION

Liquid metal facilities and experiments require specialized sensors and diagnostics, particularly for air- and moisture-sensitive alkali metals such as sodium. The high-temperature and corrosive environment of liquid metals severely limit the available component and instrument material options. Traditional temperature measurement techniques such as thermocouples offer excellent compatibility and reliability but are not scalable to provide high-density measurements suitable for computational fluid dynamic code validation. High resolution measurements of velocity and temperature are typically obtained via optical techniques, but these are unsuitable for opaque fluids such as liquid metals.

An excellent overview of liquid metal level sensor technology can be found in the AEC Report by Slocomb [1]. Though the title of the nearly 60 year-old report includes the words “state-of-the-art”, few level technologies have been developed since. Sodium and other liquid metals have very good electrical conductivity which is leveraged in a number of measurement techniques. The most common conductivity-based level measurement techniques being point contact, resistance, and inductive type sensors [1]. Float [1], ultrasonic [1,2], and gamma ray absorption [1,3] techniques have also been used historically.

Laser distance metering, developed since the Slocomb [1] paper, has been used in liquid metal and foundry applications [4,5]. A laser diode coupled with a co-located receiver enable non-contact liquid level measurements with accuracy down to 2 mm. The laser sight glass design is the primary challenge with decreased performance as sodium vapor condenses on the glass.

Additional newly developed or improved liquid metal level sensors include noncontact capacitance-level transducers [6], Fiber Bragg Grating sensors [7], and magnetic induction tomography [8].

This paper describes high-resolution liquid-sodium temperature and level measurements using Rayleigh-backscatter-based distributed fiber optic temperature sensors [8-11]. These distributed temperature sensors (DTSs) have been shown to function well at temperatures up to 600 ˚C [12], and on the exterior of sodium piping for leak detection [13], but not yet immersed in a liquid sodium environment.

2. TEMPERATURE SENSING WITH OPTICAL FIBERS

Computational fluid dynamics and other sophisticated modeling techniques aid the analysis and design of engineering systems. To continue their development, these codes require new types of validation data to reach full maturity. Numerous new techniques have been developed over the last few decades to meet this new validation challenge. Many high-resolution measurement techniques are unsuitable for an optically opaque, high temperature, and corrosive environment like liquid sodium. Distributed temperature sensing based on Rayleigh scattering and swept-wavelength interferometry was identified as a promising candidate to provide high-resolution temperature data in liquid sodium [11]. Thousands of temperature measurements can be acquired along a single strand of thin optical fiber, which is called a distributed temperature sensor (DTS). This sensing principle has been used to measure temperatures near the core of a research reactor [10].

A basic description of the DTS technique used in SNAKE is included here while a detailed description can be found in [11,14,15].

Light travelling through a fiber optic waveguide is scattered by impurities and structural variations at the molecular level. The random, inhomogenous distribution is stable, giving rise to a backscatter pattern that is unique to a single fiber. The spectrum and amplitude of the pattern can be read to serve as a fiber signature and used to interrogate the state of the cable. Physical changes such as strain and temperature shift alter the signature in a repeatable way, and detecting this is the basis for using the fiber as a sensor.

A tunable laser sends a narrow band signal into the fiber for the purpose of obtaining the resultant backscatter [9]. This scattering signal is mixed with a reference signal to generate an interference pattern at the detector. The signal is Fourier transformed to obtain the location of the scattering centers. The amplitude of the backscatter as a function of wavelength, λ, is extracted and cross correlated with a baseline signal, or tare. Spectrum shifts are proportional to the strain and temperature according to [9]:

$$\frac{\Delta\lambda}{\lambda} = K_T \Delta T + K_\varepsilon \varepsilon \quad (1)$$

where K_T and K_ε are the temperature and strain coefficients, respectively. K_T includes coefficients for thermal expansion and the index of refraction. The thermal expansion coefficient varies with fiber and coating composition and is on the order of $8x10^{-6}$ K^{-1} for silica fibers.

3. DEMONSTRATION OF LEVEL MEASUREMENT TECHNIQUE

Sodium vessels are maintained at elevated temperature, above 150 ºC, and are typically only partially filled with sodium. Cover gas flow is maintained above the sodium at pressures slightly above atmospheric to provide positive pressure and ensure that air and humidity does not enter the vessel. Oxidation and fluid chemistry is strictly controlled in liquid metal systems to prevent plugging, carburization, and property degradation. The cover gas purge is often introduced at approximately room temperature but is gradually heated as it flows along the vessel walls, contacts the free surface of the sodium, and self-mixes.

Due to the superior thermal properties of sodium, the mean cover gas temperature is typically at a lower temperature than the mean sodium temperature as long as a constant gas purge is maintained. This presents an interesting opportunity to detect the sodium-gas interface with a temperature sensor of suitable resolution.

A proof-of-concept level measurement setup was assembled in order to confirm the feasibility of simultaneous measurement of temperature and level with a DTS. The demonstration setup (see Figure 1) consisted of a stainless steel capillary with embedded DTS sandwiched between two heated copper slabs simulating the high-conductivity liquid metal. The top portion of the capillary protruded from the slabs into air at ~20 ºC which simulated the cover gas. Nominal laboratory ambient air circulation was used to cool the protruding capillary to simulate low flowrate cover-gas purges typical of alkali metal systems.

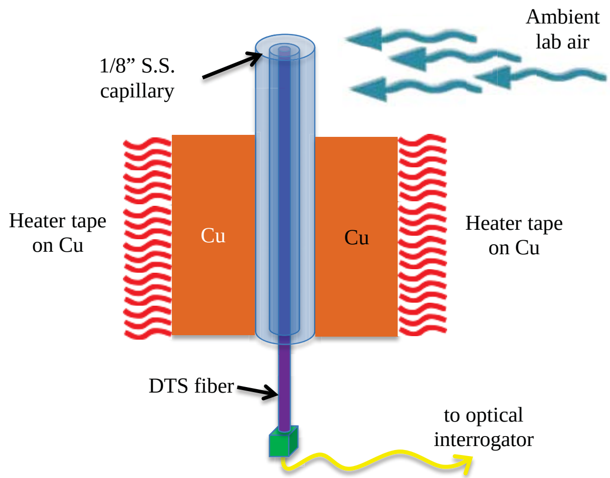
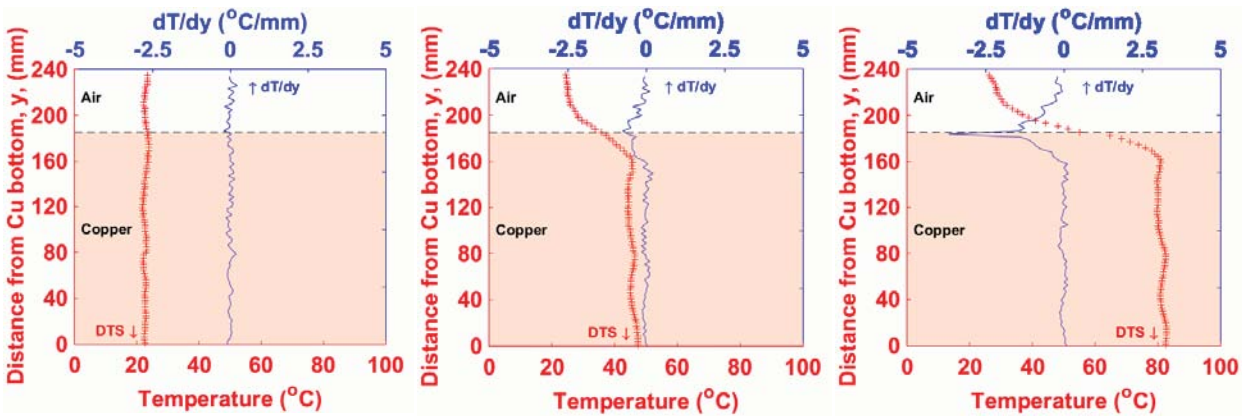


Figure 1: Proof-of-concept DTS level measurement setup. Stainless capillary containing the DTS was sandwiched between two heated copper slabs. The top portion of the stainless capillary and DTS protruded from the copper slabs and was cooled by nominal laboratory ambient air.

Results of the proof-of-concept DTS level measurement setup are shown in Figure 2. The temperature difference, ΔT, between the laboratory ambient air, T=22 ˚C, and the copper slab was maintained at three different values for Figure 2(a) through (c). Each plot shows the detailed temperature profile along the length of the fiber. As the copper slab temperature was increased, the air/copper interface became increasingly apparent. However, even for a ΔT of 24 ˚C in Figure 2(b), the gradual change in temperature made it difficult to pinpoint the exact interface location. A sharper gradient exists for a ΔT of 63 ˚C in Figure 2(c).

The gradient can be quantified by calculating the derivative, dT/dy, of the temperature data which is also plotted in Figure 2. This derivative value was essentially flat until the temperature differential between the copper slab and air was greater than ~30 ˚C due to the inherent noise in the data. Once the temperature different was large enough, peak detection could be used to locate the largest derivative value which matched the actual air/copper interface within ± 1 mm. These results demonstrated the promise of using a DTS for simultaneous temperature and level, or temperature interface, detection.

The remainder of this manuscript details use of DTS to measure liquid sodium temperature and level by extending the concepts discussed here to sensors deployed in a sodium experiment at Argonne National Laboratory.



(a) (b) (c)

Figure 2: Proof-of-concept level measurement setup to confirm efficacy of level measurements using a DTS. Three copper slab heat temperatures are shown in series with a temperature difference between the copper slab and laboratory ambient temperature (T=22 ˚C) was (a) ΔT=0 ˚C, (b) ΔT=24 ˚C, and (c) ΔT=63 ˚C.

4. TEMPERATURE AND LEVEL MEASUREMENT IN LIQUID SODIUM

The Argonne S-CO_2 - Na Kinetics Experiment (SNAKE) apparatus [16] was used as a test bed for DTS measurements in liquid sodium. The SNAKE program primary mission is to study the nature and extent of chemical reactions occurring when high-pressure CO_2 is injected into liquid sodium. The DTS was adopted for high resolution temperature measurements around the CO_2 jet. Sodium-CO_2 chemical interactions are being studied to characterize safety and operational issues of a supercritical carbon dioxide (sCO_2) Brayton cycle coupled with a Sodium-Cooled Fast Reactor (SFR). This application of the sCO_2 energy conversion cycle is expected to improve the safety and economics of SFR designs. More information can be found in Gerardi et al. [16].

The sodium vessel (Figure 3) used in the SNAKE experiment presented a convenient location to demonstrate the feasibility and usefulness of advanced sodium instrumentation such as the DTS.

The optical fiber sensing system used for this study was an ODiSI (Optical Distributed Sensor Interrogator) model B from Luna Innovations, Inc. (Roanoke, VA), configured to handle sensors up to 10 m in length with a 2.56 mm spatial resolution at data rates up to 100 Hz and a temperature span of -268 to 900 ˚C, though the sensor itself is likely to have a smaller service temperature range.

The DTSs were also manufactured and assembled by Luna Innovations. Fiber optic cables were stripped of all coatings using a sulfuric acid bath to obtain bare glass fibers with 125 µm diameter. A cobalt high-temperature end termination was installed to enable sensing. Without a coating, the bare fibers are extremely fragile so they were installed into Ø 360 µm OD, Ø 160 µm OD silica capillaries and sealed.

At Argonne, the silica capillaries with internal DTS were placed into Ø 1.59 mm OD, Ø 0.056 mm ID stainless steel tubing. This DTS configuration can be used reliably up to 600 ˚C [12] and has been extensively evaluated for temperature measurements by the Argonne group [11,12,14,15].

Two DTSs, shown in Figure 3(b), were used to simultaneously measure temperature during the filling and draining of sodium from the vessel. Calibration was performed using the oven setup reported in [12] to relate wavelength shift to temperature shift from a baseline signal. The first DTS was placed inside a stainless steel capillary extending from the top of the vessel and parallel to the thermocouple rake. This DTS measured sodium column temperature.

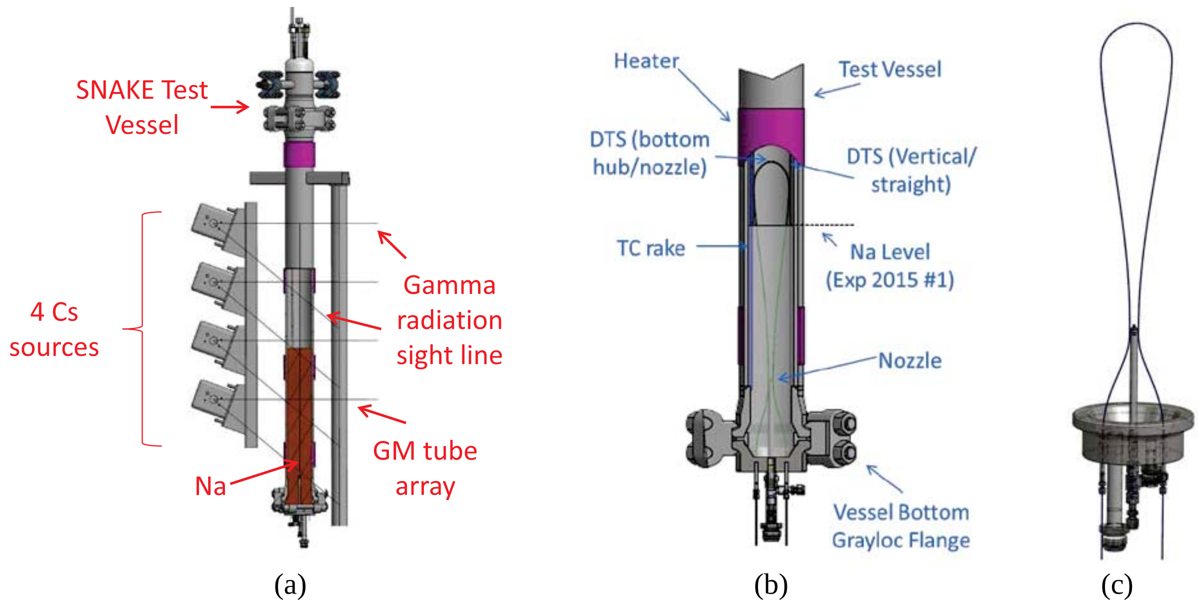


Figure 3. SNAKE test vessel drawings: (a) vessel and gamma level detector; (b) nozzle, thermocouple rake, and DTSs; (c) standalone image of the bottom hub and attached nozzle DTS in capillary

The second DTS was positioned near the nozzle of the sCO_2 injector to measure jet temperatures with high-resolution (Figure 3(c)). The capillary enters and exits the sodium vessel from the bottom of the vessel hub to facilitate installation and allow a single DTS to measure the jet temperature on two sides of the nozzle. The DTS capillary is fixed to the nozzle for lateral support and extends vertically at an angle following the estimated gas jet cone angle, providing measurements in the sodium just adjacent to the gas jet. The geometry of the capillary configuration was measured in detail prior to installation into the SNAKE test vessel and used to map temperatures onto a 2D surface, discussed below, using a custom MATLAB script. This sophisticated mapping of temperatures can be extended to 3D surfaces and would be advantageous even in a transparent fluid since most optical temperature diagnostics are point, straight-line, or planar techniques.

Accuracy of the DTS measurement technique was evaluated using two supplementary level sensors. A single-point contact-type probe that electrically shunts when sodium contact is made was placed at 1.197 m above the nozzle. A gamma level absorption non-contact instrument was installed exterior to the vessel. The Tracerco LevelFinderPlus [3,17] was selected to measure sodium level in SNAKE. It consists of four small cesium-137 sealed-sources (each 7.4 MBq). These sealed-sources are placed in shielding containers equipped with a shutter to enable a collimated gamma beam to shine through the SNAKE test vessel toward an array of ten Geiger–Müller (GM) tubes. The radiation detected by the GM array can be linearly related to the sodium level in the test vessel as the sodium rises and blocks a portion of the radiation. Uncertainty in level measurements using this instrument is ± 50 mm.

4.1. Sodium Filling and Draining

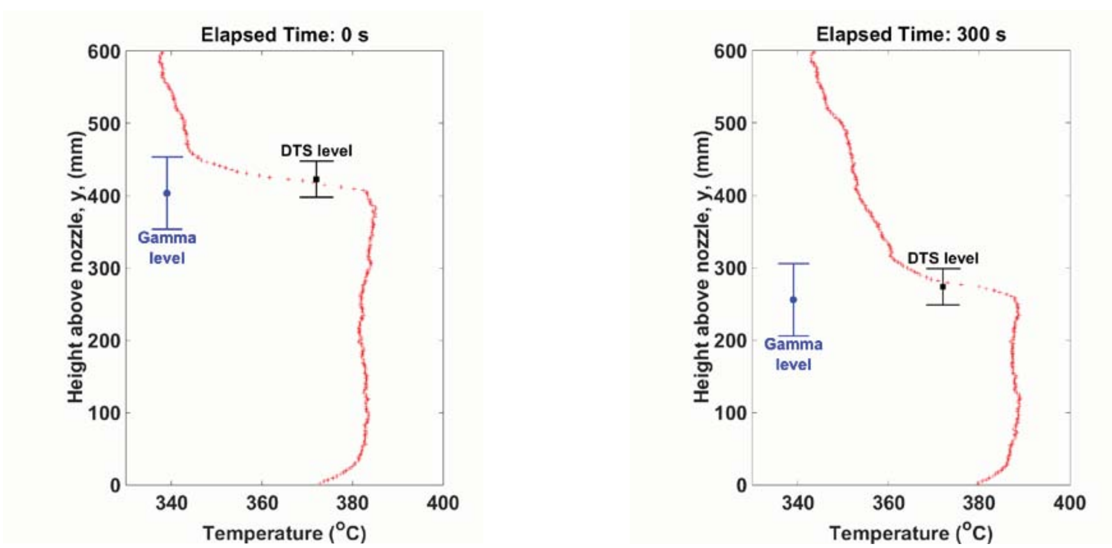
The filling phase of any liquid sodium apparatus is typically an important event that demonstrates assembly completion and the start of operations. Sodium level is a critical operational parameter and so an operator should have rapid feedback on sodium height during a filling or draining operation.

The DTSs installed in SNAKE were monitored during several sodium fill and drain operations to assess the viability of using a DTS to measure sodium temperature and level.

During each fill phase, the sodium level was raised to the height of the single-point contact-type probe to verify that the maximum level reading of the DTS level technique was correct and to calibrate the gamma absorption level meter span. The vessel was then drained while all level measurement sensors were monitored. This was repeated several times. A single drain operation and fill operation are discussed in detail below.

4.1.1. Level and Temperature Measurement with Cover Gas Flow

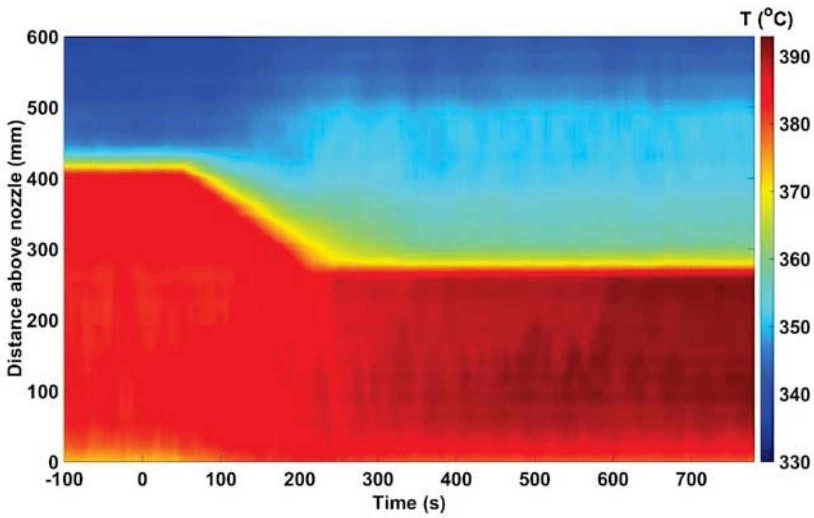
The vessel was drained while monitoring the long straight vertical DTS configuration with data shown in Figure 4. Draining was completed with a 15 slpm argon cover gas maintained over the test vessel. Sodium temperature was maintained at 387 ºC, while the cover gas was introduced into the vessel at room temperature, 25 ºC, and was heated to 340 ºC by the time it reached the sodium interface. As shown in Figure 4, this temperature gradient was detected and could be tracked as sodium was drained from the test vessel. DTS level was determined using automatic peak detection of dT/dy as discussed in Section 3 for the Cu slab. The gamma level meter reading is also included in Figure 4.



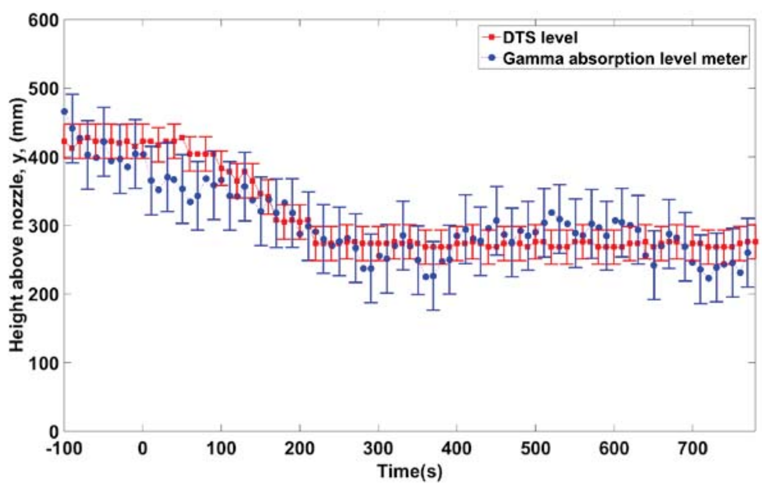
(a) (b)

Figure 4: Sodium level measurement using the vertical DTS during sodium draining. (a) Prior to draining with a sodium level of (422 ± 25) mm and (b) after the sodium level decreased to a height of (275 ± 25 mm). DTS sodium level estimate and gamma absorption level meter measurement are also shown. The sodium was at ~387 ˚C, while the argon cover gas was at ~ 340 ˚C.

At time zero, the sodium level was approximately (422 ± 25 mm) above the nozzle and subsequently drained to (275 ± 25 mm). Prior to draining, the temperature gradient was extremely sharp, approximately 40 ºC in 46 mm or a slope of 0.86 ºC/mm. During draining, at 300 s when the sodium level reached the desired set point of 275 mm, the temperature gradient was reduced to 28 ºC across 61 mm for a slope of 0.45 ºC/mm. This reduced slope was likely caused by the slow gas response time of the transient drain operation and by the sodium film that remains on the DTS capillary after draining. This film would be present if the sodium wetted the capillary and would slowly slide down the capillary as long as it remains molten. These two issues were not and would not be observed during a fill operation since the high heat transfer property of sodium enables the rapid response time which results in an immediate sharp gas - sodium interface.



(a)



(b)

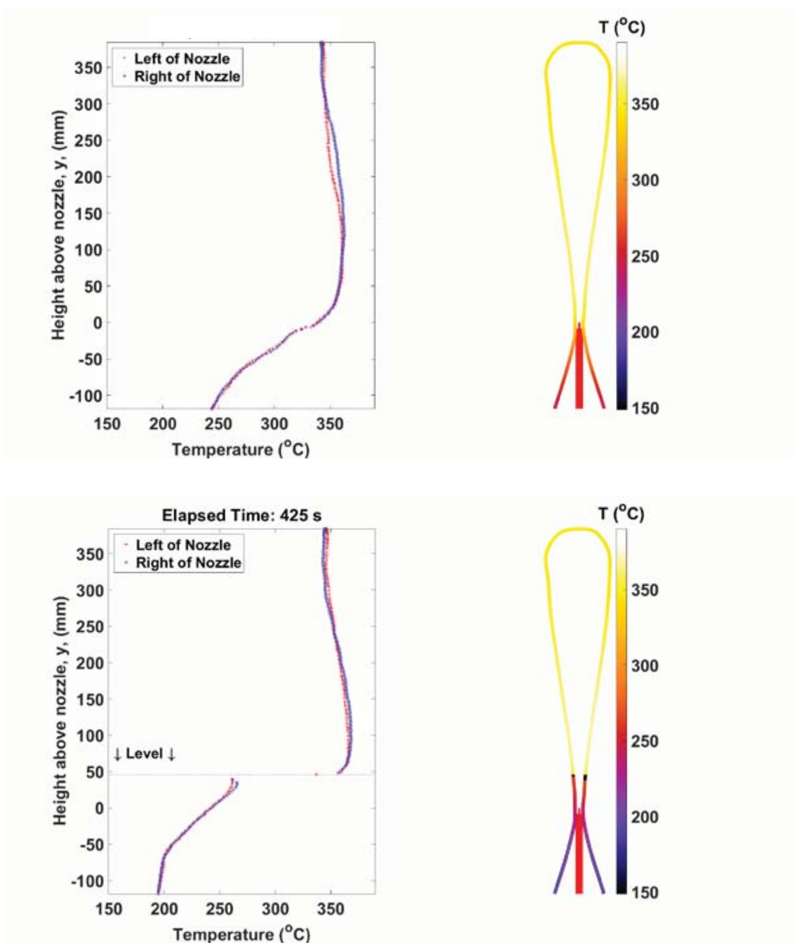
Figure 5: Sodium level as a function of time shown as (a) DTS raw data as color contour, and (b) DTS level detection using interface location scheme compared to gamma level meter. Note how yellow, high gradient region of contour corresponds to interface location in plot (b).

The large quantity of data produced by the single DTS during the draining is shown in Figure 5(a). The x-axis represents time and y-axis represents height above the nozzle. Color intensity is used to represent temperature. Measurement frequency was 100 Hz which accounts for the high data density in the x-axis.

The DTS spatial (y-axis) resolution was 2.68 mm. The drop in sodium level from time zero to time 250 s was clearly observed and was approximately represented by the interface of the bottom region in red. The gamma level meter measurements are compared with the DTS level estimate technique in Figure 5(b). DTS data lies within the uncertainty band of the gamma level meter data. The mean values of the gamma and DTS measurements during the steady-state period between 200 s and 800 s was 272.1 and 273.0 mm, respectively. Uncertainty in both is higher than conventional instruments used in common applications such as ΔP water level, but compares well with the techniques detailed in Slocomb [1].

4.1.2. Level and Temperature Measurement without Cover Gas Flow

The vessel was filled while monitoring the bottom-hub curved DTS configuration with the test vessel pre-heated to a nominal temperature of 350 ºC. Figure 6 shows the temperature profiles of the bottom hub DTS configuration prior to and during this fill operation. Prior to filling, there is a temperature gradient below the nozzle due to insufficient heating and associated losses from the bottom of the test vessel. A large temperature gradient is clearly discernable at ~ 50 mm above the nozzle at 425 s after the start of filling. The color contour versions of the fiber shape shown on the right side Figure 6 could be easily used by an operator during a filling operation to roughly achieve the desired sodium level.



(a)

(b)

Figure 6: Sodium level using the bottom hub DTS. (a) Empty vessel at ~ 350 ˚C; (b) sodium fill at ~150 ˚C to a level of 50 mm.

No cover gas flow was applied during this fill operation in order to evaluate the effectiveness of DTS level measurement without significant temperature differential between gas and sodium. The initial sodium temperature during fill was low, around 150 ºC which created an observable temperature difference initially between the DTS and fill sodium. However, since the thermal conductivity of sodium was so high, it quickly heated to the test vessel temperature. Since there was no cover gas flow to keep the cover gas temperature lower than the sodium temperature, the sodium quickly equilibrated with the vessel and cover gas. At times later than 600 s (not shown) there was not a large enough temperature gradient at the gas/sodium interface to facilitate level measurement. Thus, maintenance of a cover gas purge was critical to successful DTS measurement of sodium level.

4.2. Expected response of fibers in sodium

The response time of the DTS to sodium temperature fluctuations was estimated by calculating the time constant of heat transfer from sodium to the fiber. The steel capillary enclosing the fiber will be the source of highest thermal resistance, thus the measurement was assumed to be taken at the center of a solid stainless steel rod with the same OD of the stainless capillaries, 1.59 mm. This was considered a rough estimate of the time constant. The time constant, τ, was obtained using the transient 1D conduction equation for an infinite rod. Better estimates would be obtained by considering the complex geometry of the stainless steel capillary, air gap, silica capillary, second air gap, and fiber. For the portion of the DTS immersed in sodium the calculated time constants are 7.1 ms and 8.9 ms for sodium velocities of 0.5 m/s and 0.01 m/s, respectively. For the portion of the DTS that was exposed to the argon cover gas, the time constant was 17 s, and 6.0 s for a gas velocity of 1 m/s and 10 m/s, respectively. The response time in the sodium is more than satisfactory for most applications including level sensing while the calculated time response in the gas is poor. In practice, the time response in the gas was on the order of 5 s which corresponds with the higher gas velocity.

5. SUMMARY

Liquid metal facilities and experiments require specialized sensors and diagnostics, particularly for air-sensitive metals such as sodium. Rayleigh-backscatter-based distributed fiber optic sensors were immersed in sodium to obtain high-resolution liquid sodium temperature measurements. These distributed temperature sensors were observed to function extremely well at high temperatures, up to 400 ˚C, in a liquid sodium environment. The DTSs were used to measure sodium column temperature and the temperature of a complex geometrical pattern that leveraged the flexibility of fiber optics. The ability to clearly detect interfaces (e.g. sodium level) while simultaneously measuring temperature with the same sensor was confirmed. Maintenance of a cover gas purge was critical to successful DTS measurement of sodium level in order to create a substantial temperature gradient for automatic interface detection. Time responsivity could be further increased by reducing the fiber and external capillary diameters or by using alternate materials. Future work is necessary to assess DTS capabilities beyond their current 600 ˚C operating limit and in further evaluating their time response in engineering environments.

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