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Experimental Study of Cryogenic Fill-Level Sensors for Liquid Hydrogen Aircraft Applications

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INTRODUCTION & AIM

The safe and **accurate fill level measurement of liquid hydrogen** (LH_2) is a critical enabling technology for the adoption of hydrogen as a sustainable aviation fuel. Several LH_2 fill level measurement techniques have been applied in industrial, automotive, and space applications, however no system has yet been validated at the scale, robustness, and precision required for modern aircraft Fuel Quantity Indication Systems (FQIS).
The **certification frameworks**, specifically *ISO/AWI 19888-1 (Hydrogen Technologies - Aerial Vehicles - Part 1: Liquid Hydrogen Fuel Storage System)* have yet to be formally ratified, therefore *ISO 13984 (Liquid hydrogen – Land vehicle fueling system interfaces)* can be used in combination with *ARINC 611-1 (Guidance for the Design and Installation of Fuel Quantity Systems)* and specific tank geometries as presented in the *DLH25* hydrogen aircraft concept to derive the requirements for the FQIS. This study investigates whether current sensor layouts can satisfy the mandated accuracy requirement of $7\,mm$ [2].

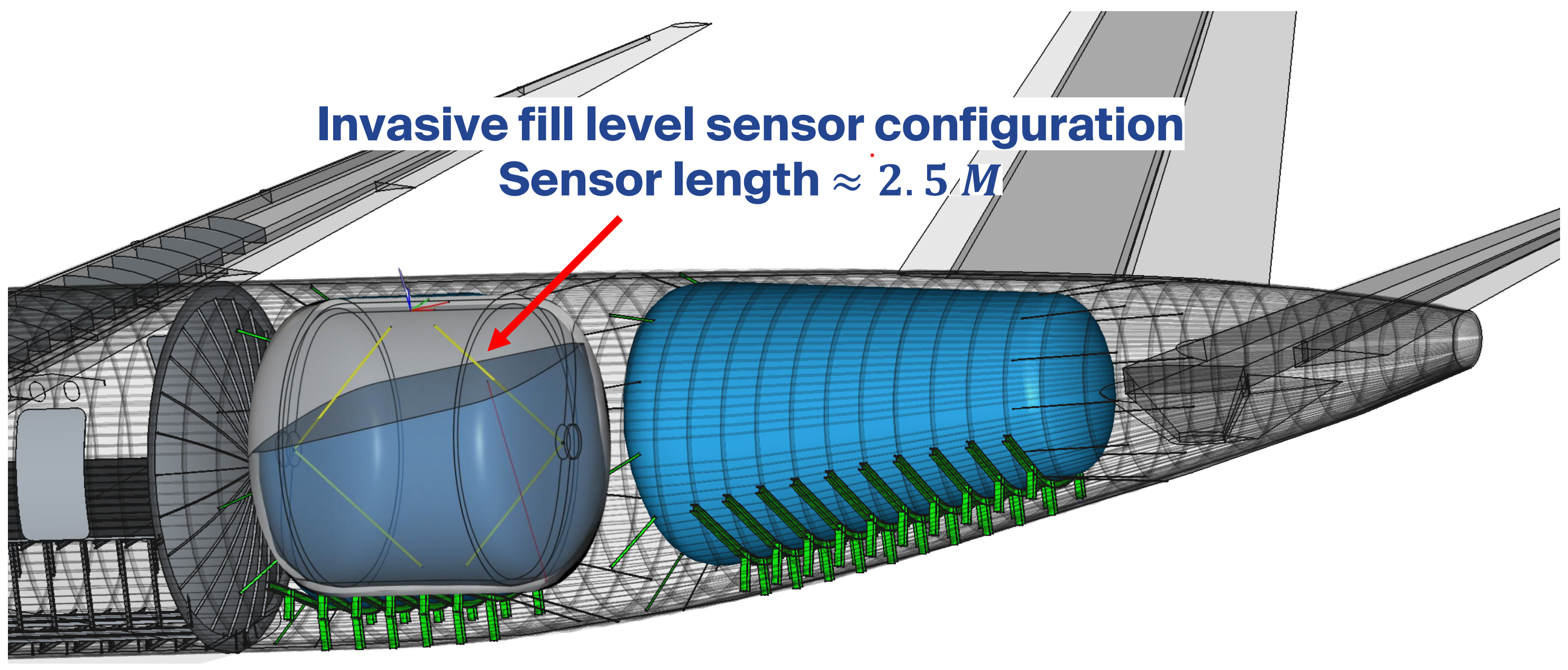

Fig.1: LH_2 tank placement of the *DLH25* concept, produced by the authors based on geometry data from Kotzem et al. (2024) [1] with visualization of fill level sensor configuration.

METHOD

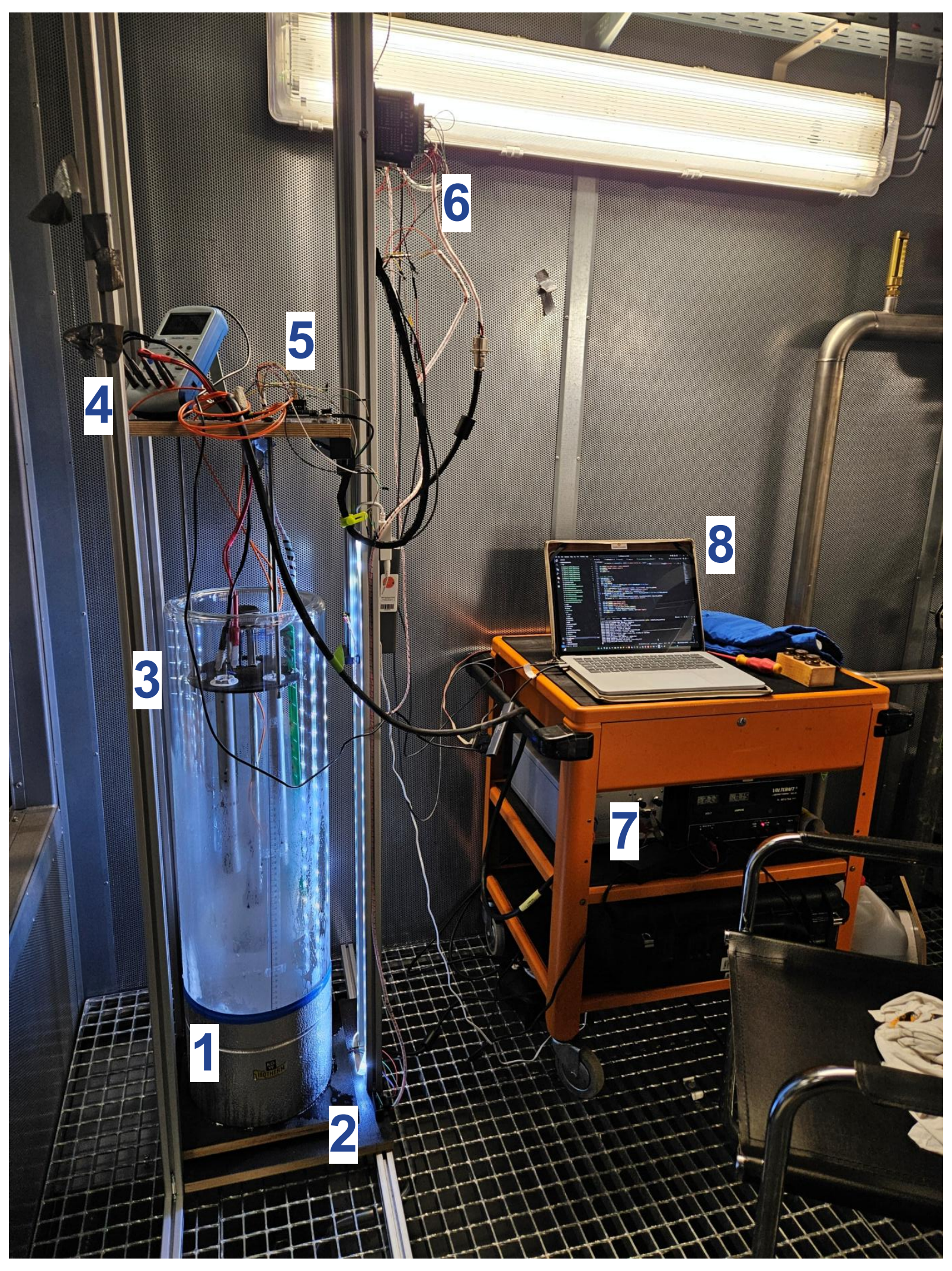

Fig. 2: Testbed setup
(1) Transparent cryostat, (2) load cells,
(3) movable sensor platform, (4) LCR meter,
(5) interface, (6) motor controller,
(7) laser interferometer, and (8) workstation.

In this study, liquid nitrogen (LN_2) was utilized as a cryogenic substitute for LH_2. Although its boiling point of $-196°C$ is higher than that of LH_2 $(-253°C)$, LN_2 remains a suitable medium for evaluating sensor performance within cryogenic environments.
At the center of the experimental setup, a transparent cryostat is integrated with a vertical linear actuator, providing a positioning accuracy of $0.04\,mm$. This configuration not only enables precise sensor submersion, automated cycling, and data acquisition at varying speeds but also allows for direct observation of the sensors during the submersion process. In addition to manually reading the fill level from a ruler, load cells are utilized to monitor the liquid level and boil-off rate. Figure 2 shows the complete testbed setup. In this study, the scaled sensor prototypes were submerged for 20 cycles at a speed of $1\,cm/s$, with a 5-second pause at each turnaround point.

While there are many possible sensor designs to gauge LH_2, this study aims to compare promising capacitance sensor designs, investigate resistive thermal devices (RTDs) and a sensor based on optical absorption.

RESULTS & DISCUSSION

Capacitance Probes

Capacitive probes measure the fill level in a tank by detecting changes in capacitance, which is proportional to the permittivity of the medium in the probe's electric field as shown in the following Equation.

$$C(h) = K_{Sensor} \cdot (\varepsilon_{r,g}\,(H - h) + \varepsilon_{r,l} \cdot h) + C_{off}$$

Cylindrical probes are commonly used in aircraft fuel tanks. However, the difference in permittivity between JET A-1 and air is approximately five times smaller than that of LH_2 and GH_2, resulting in reduced sensor sensitivity. To increase sensitivity, the probe diameters can be increased; alternatively, if integration space is limited, multiple concentric cylinders can be introduced where every second cylinder is electrically coupled.

$$\mathrm{K}_{Cylindrical} = \sum_i \frac{2\pi\varepsilon_0}{\ln\left(\frac{r_{i+1}}{r_i}\right)}$$

We investigated a two and a three-cylinder capacitance probe with radii of $15.3\,mm$, $22\,mm$ and $29\,mm$. By adding the third cylinder the sensitivity increased by 250%, however Table 1 shows that the root mean square deviation($RMSD$) and Signal-to-noise-Ratio (SNR) was only marginally improved.

A **fringing field sensor** measures the change in permittivity perpendicular to its electrodes, which allows for a more flexible sensor design, non-invasive measurements, and direct integration into tank wall structures. The geometric capacitance factor of a fringing field sensor can be approximated as follows:

$$\mathrm{K}_{\mathrm{Fringing}} = \frac{\varepsilon_0}{pi}\ln\left(\left(1+\frac{w}{a}\right)+\sqrt{1+\left(\frac{w}{a}\right)^2-1}\right)$$

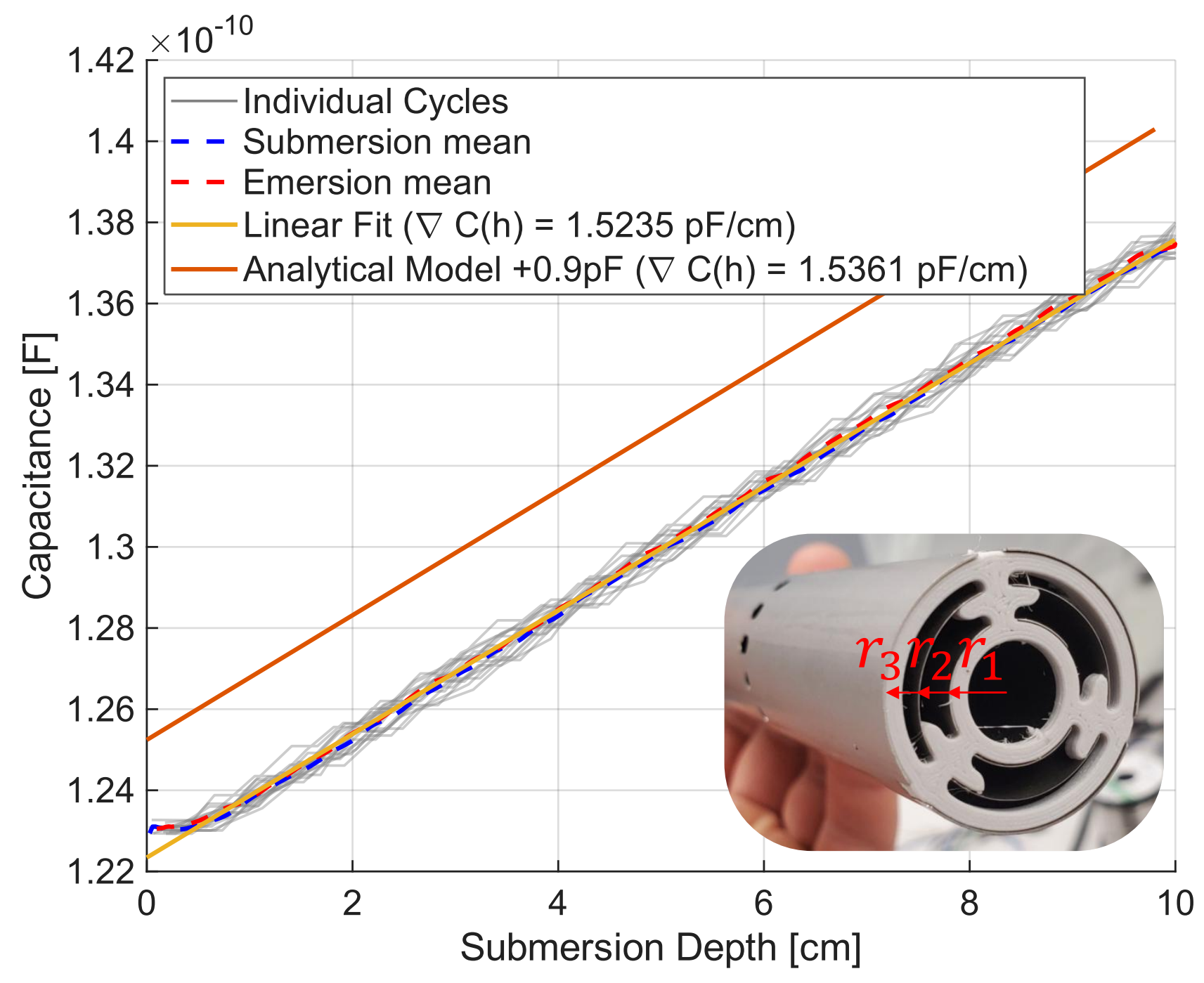

Fig. 3 Capacitance 3-cylinder probe test data

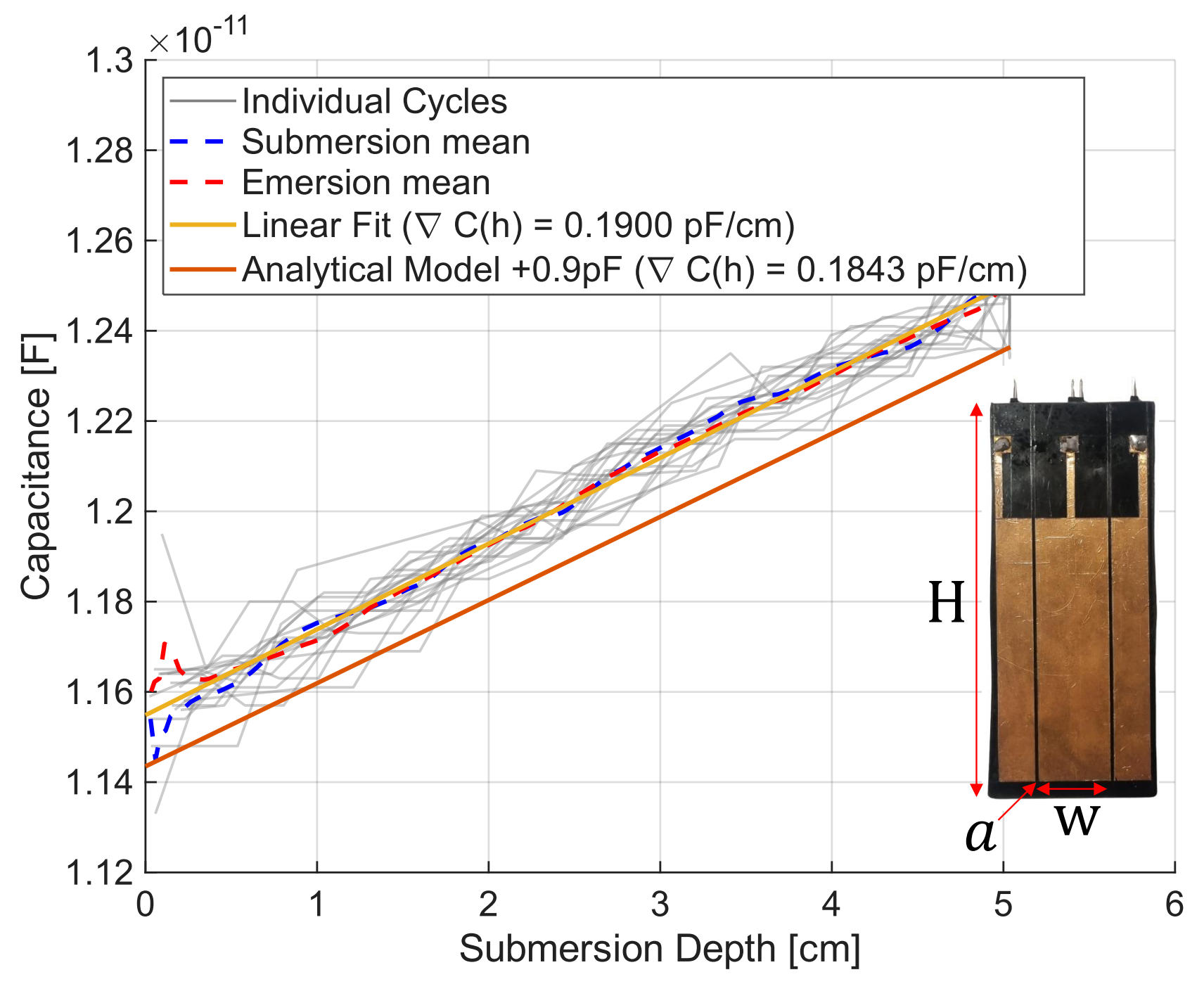

Fig. 4 Capacitance fringing field probe test data

TAB. 1 Quantitative comparison of probes

Sensor	$RMSD$	SNR	Δh_{total}
2-cylinder probe	0.11 pF	502.26	5.29 mm
3-cylinder probe	0.25 pF	529.60	5.06 mm
Fringing-field sensor	0.07 pF	177.52	6.03 mm

Optical Absorption Sensor

The optical absorption sensor consists of a laser interferometer that emits laser pulses at a wavelength of $850\,nm$. These pulses are guided through optical fibers to the probe, where they propagate freely through a hollow steel cylinder and the amplitude of the returning pulse is measured. Compared to other optical gauging methods like the fiber-Bragg grating, this method requires no active heating. In LN_2 no significant correlation was observed between the submersion depth and Interferometer reading. A subsequent test with H_2O confirmed the sensor was not damaged during the cryogenic test. The spikes in the interferometer reading are caused due to the sensor geometry and were consistently reproducible.

Resistive Temperature Device

Resistive Temperature Detectors (RTDs) are commonly used in space applications to monitor cryogenic fuels at discrete levels. While passive RTDs can be used for fill-level detection, the lack of a significant temperature gradient between the liquid and gas near the interface limits their precision; therefore, actively heated elements are preferred. In this study, an RTD rake was designed utilizing ten PT-1000 elements paired with $220\,\Omega$ heating elements and a MOSFET to induce precise heating pulses. Observations indicated that a heat impulse of $2.62\,W$ enables clear identification of the liquid level after $1.5\,s$. The heating elements and sensors were thermally coupled using thermally conductive paste. Following LN_2 submersion, cracks were observed in the hermetically seal, as shown in Figure 6. However, the substrate showed no signs of fatigue and the functionality remained.

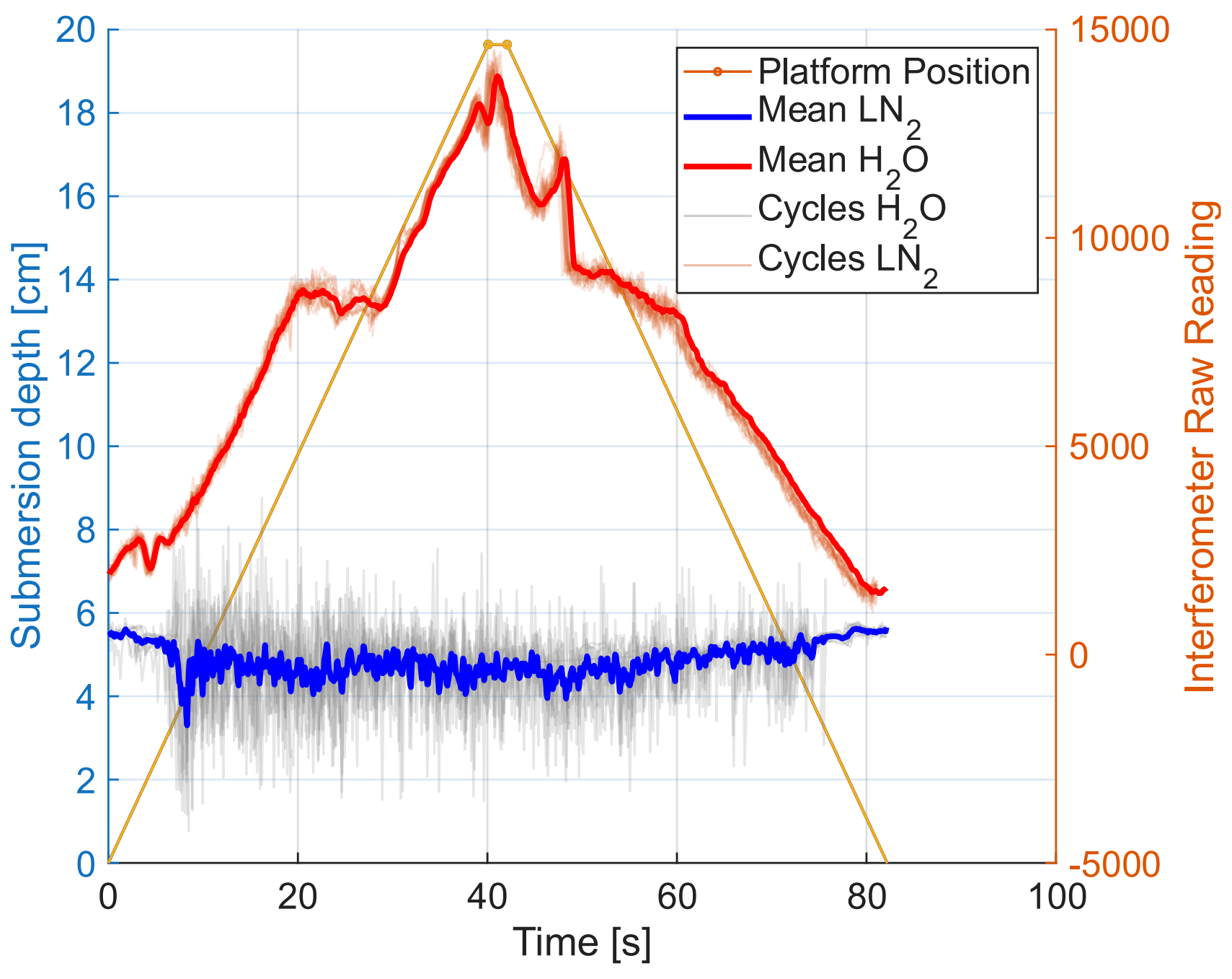

Fig. 5 Optical sensor characteristic

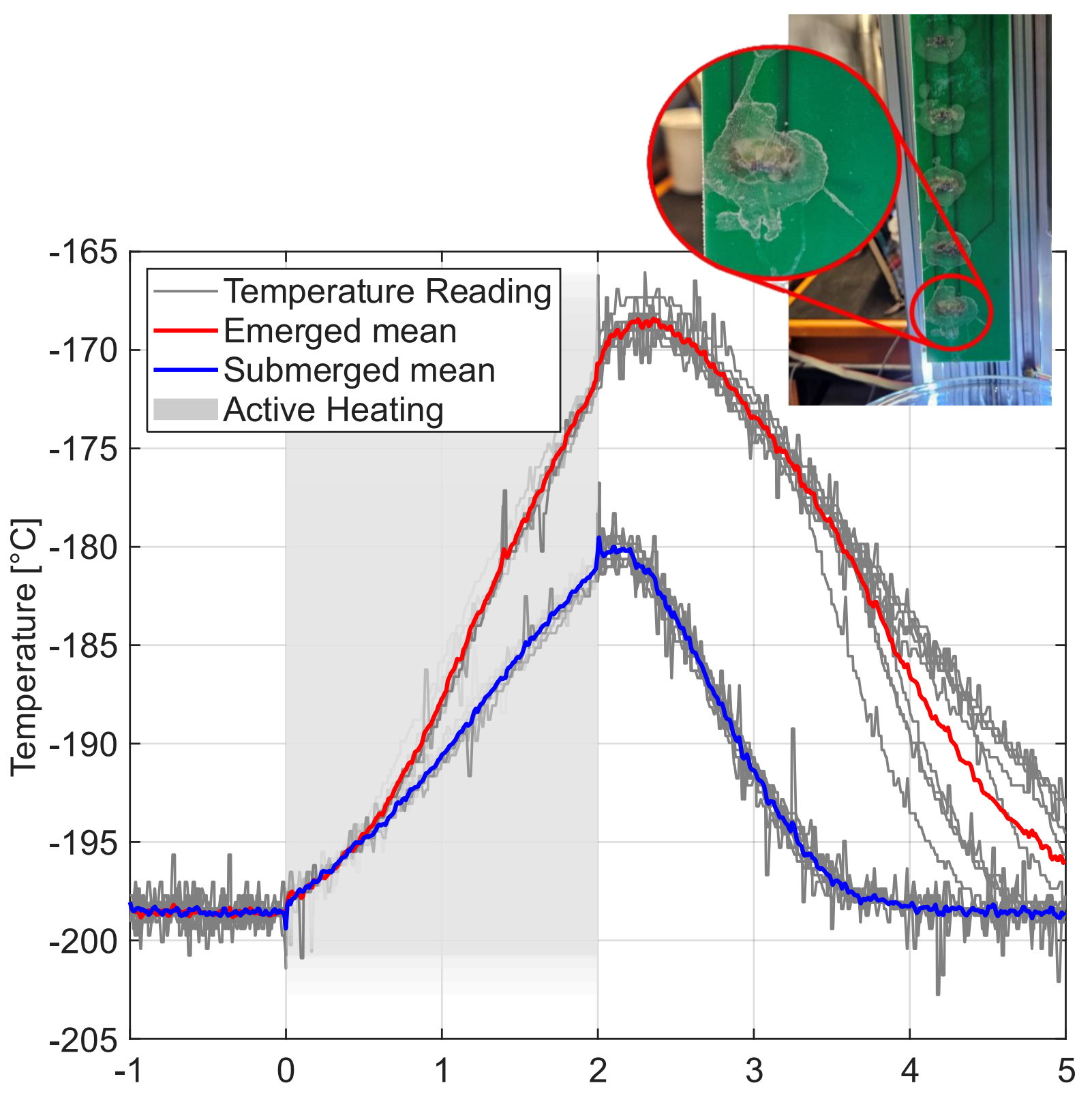

Fig. 6 PT-1000 characteristic after LN_2 submersion (heat impulse of 2.62W)

CONCLUSIONS / FUTURE WORK

Both the **fringing field sensor** and **cylindrical capacitance probes** exhibited characteristics that closely matched analytical predictions. However, the Signal-to-Noise Ratio improved less than expected when adding a third cylinder to the cylindrical probe; this suggests that the noise is likely not capacitance sensitivity, but rather by physical fluctuations in the liquid, such as bubbles caused by boiling. While an accuracy of $5.06\,mm$ was demonstrated in nitrogen, it is predicted that the less pronounced change in permittivity in hydrogen will result in an accuracy of $10.8\,mm$ [2]. This necessitates a more optimized design to meet the accuracy requirement.
Tests with an **optical absorption sensor** demonstrated that while it remained functionally intact, it is not suitable for gauging LN_2 or LH_2, as neither liquid exhibits a significant electromagnetic absorption coefficient in the near-infrared spectrum.
Conversely, an **RTD rake** was able to track the liquid-gas interface reliably and is expected to operate with even shorter or weaker heat pulses when gauging liquid hydrogen.

NOMENCLATURE / REFERENCES

a	Size of the gap
C	Capacitance
C_{off}	Capacitance Offset
$\varepsilon_0, \varepsilon_{r,l}, \varepsilon_{r,g}$	Vacuum, liquid, gas permittivity
h, H	Liquid level, sensor height
Δh_{total}	Total sensor accuracy in mm
K_{Sensor}	Geometric capacitance factor
r_i	Radius of the cylinder
w	Width of electrode

[1] M. Kotzem, S. Wöhler, T. Burschyk, C. Hesse, and S. Hellbrück, Conceptual Aircraft Design of a Research Baseline with Direct Liquid Hydrogen Combustion, ICAS, https://www.icas.org/icas_archive/icas2024/data/papers/icas2024_0503_paper.pdf.

[2] A. J. O. Winter and K. Kochan, Liquid Hydrogen in Aviation: A Critical Review of Usage and Level Sensing Technologies, Progress in Aerospace Sciences https://doi.org/10.1016/j.paerosci.2026.01205.

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