ADVANCED SENSOR TECHNOLOGIES FOR CRYOGENIC LIQUID PROPELLANT FLOW PHENOMENA

Mr. Martin Siegl
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Germany, martin.siegl@dlr.de

Mr. Alexander Fischer
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Germany, alexander.fischer@dlr.de

Dr. Jens Gerstmann
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Germany, jens.gerstmann@dlr.de

Mr. David Becker
Coburg University of Applied Sciences and Arts, Germany, david.becker@hs-coburg.de

Ms. Katrin Schmidt
Coburg University of Applied Sciences and Arts, Germany, katrin.schmidt@hs-coburg.de

Prof. Gerhard Lindner
Coburg University of Applied Sciences and Arts, Germany, gerhard.lindner@hs-coburg.de

Mrs. Alice Fischerauer
University of Bayreuth, Germany, alice.fischerauer@uni-bayreuth.de

Mr. Christoph Kandlbinder
University of Bayreuth, Germany, christoph.kandlbinder@uni-bayreuth.de

Prof. Gerhard Fischerauer
University of Bayreuth, Germany, gerhard.fischerauer@uni-bayreuth.de

Sensors for various fluid physical quantities play a vital role in the management of cryogenic liquid propellants (hydrogen, oxygen, methane), used worldwide in launchers such as the European Ariane rockets. In addition, measurement devices are particularly central in all basic scientific fluid experimentation, investigating for instance liquid sloshing, free liquid surface movement, boiling or bubble formation. The results of these experiments in microgravity and on ground enable the efficient design of present-day cryogenic launcher (upper) stages and (as possible future applications) of long-term orbital propellant storage facilities, in-orbit refuelling stations and interplanetary cryogenic propulsion. These utilizations call for sensor technology to efficiently perform propellant mass gauging, determine fill-levels, temperature fields, phase change quantities and bubble formation in a non-intrusive fashion. An overview of various candidate cryogenic sensor technologies currently investigated by the authors is provided. Tomographic techniques based on sound waves and electrostatic fields are discussed with respect to their applicability in cryogenic liquids, potential applications areas, engineering challenges and corresponding validation tests. Fibre-optic technologies for visual observations and large scale, high resolution distributed temperature measurements are presented with first results of their validation in cryogenic liquids. New and improved insights into cryogenic liquid propellant behaviour are possible, as is shown based on experimental applications.

I. INTRODUCTION

Efficient management of cryogenic liquid propellants (hydrogen, methane and oxygen) plays a pivotal role in the operation of launchers and particularly their cryogenic upper stages. Flexible re-ignition capability of these cryogenic upper stages could enable complex multi-orbit mission scenarios but poses significant additional propellant handling challenges during and after free-flying coast phases, when fuel tanks are partially depleted at restart.

Upper-stage cryogenic re-ignition capability is part of the goals of Ariane 6 development, offering apogee-kick manoeuvres (e.g. from geostationary transfer orbits, GTO) and stage deorbiting for debris mitigation.

Moving the focus from present day launchers to long-term space travel prospects, advanced propellant management techniques would also be required for the efficient operation of space-borne cryogenic propellant depots offering spacecraft refuelling.

After validation through laboratory and/or microgravity fluid experiments, Computational Fluid Dynamics (CFD) solvers are used for the simulation of the relevant physical phenomena in propellant tanks and launcher flight scenarios.

Sensors and measurement techniques are the key to any such validation effort, as they link experiments to CFD simulations.

The present work describes cryogenic test efforts for innovative measurement technologies not yet applied in the low-temperature liquid domain. Goals of the new techniques are either to provide additional experimental insights not available through other methods, and/or to significantly reduce the parasitic heating and intrusion into cryogenic experiment volumes.

For this purpose, it is of paramount importance to test sensors in the relevant liquid cryogen environments, e.g. liquid nitrogen (LN_2) or liquid hydrogen (LH_2) to determine performance, material compatibility and handling considerations.

Starting by summarizing CFD validation requirements, an overview of sensor technologies is given, followed by a treatment of the tests and experiments performed towards their qualification.

II. CFD VALIDATION REQUIREMENTS

For an improved insight into propellant behaviour and to enable a meaningful comparison between experimental results/flight data and CFD (Computational Fluid Dynamics) simulations, major areas of interest are liquid-gas interface topologies (free surfaces, boiling, bubble generation and growth), the corresponding phase transitions and the liquid/gas interface with the tank wall (contact angle and wetting behaviour). Fundamental to modelling these phenomena is also the accurate knowledge of the temperature field in the cryogenic volume of interest.

III. OVERVIEW OF SENSOR TECHNOLOGIES

The sensor technologies investigated as part of this work are grouped into:

- techniques observing liquid-gas interface topologies and phenomena
- techniques enabling temperature field measurements

The former techniques typically replace or enhance the information gathered from conventional cameras. Since cameras are usually highly intrusive in the experimental setup, nonintrusive tomographic technologies with little impact on fluid behaviour and parasitic heating are an asset.

The latter techniques typically replace or enhance temperature measurements from point-wise conventional thermometers (diodes, resistance thermometers) and should also reduce parasitic heating in relation to the number of sensors provided.

Liquid-gas Interface Observations

Ultrasound tomography (UST) and electrical capacitance tomography (ECT) are for the first time tested and validated in a cryogenic liquid in this work, demonstrating their potential as non-intrusive sensors for quantitative observations of fill-levels and gas bubbles.

Fibre-optic bundles are introduced into the cryogenic domain, potentially enabling the replacement of cameras from the experiment volume to the ambient laboratory environment.

Temperature Field Measurements

Quasi-continuous 1D fibre-optic temperature sensors are validated for measurements of the temperature field, to temperatures as low as 20 K in liquid hydrogen.

IV. TEST FACILITIES AND SETUP

Tests of these sensors and measurement technologies has been performed using liquid nitrogen (LN_2) and liquid hydrogen (LH_2) as test liquids in the Cryo-Lab at the DLR Institute of Space Systems in Bremen, Germany. While liquid nitrogen (LN_2) is a non-flammable, non-explosive cryogen boiling at 77 K (at 1 bar), liquid hydrogen (LH_2) is explosive and flammable with a boiling point of 20 K (at 1 bar), leading to an increased experimental and safety effort.

Additional pre-tests have been performed using storable liquids and LN_2 at facilities at Coburg University of Applied Sciences (ISAT) and the University of Bayreuth.

DLR Cryo-Lab

The DLR Cryo-Lab features a range of test stands for cryogenic propellant handling, providing research capabilities in support of future cryogenic launcher developments.

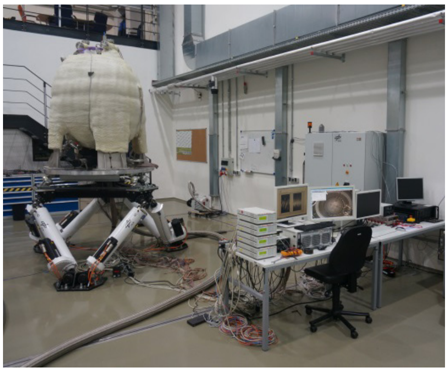

Fig. 1: Hexapod platform at the DLR Cryo-Lab, equipped with an insulated liquid nitrogen tank.

These facilities include bath submersion cryostats, a hexapod experiment platform, a tilt- and turn-table, cold heads and a vacuum chamber, operable as an explosion-proof environment.

The bath cryostat is employed in the present validation campaigns. The hexapod, tilt-table and turn-table enable the experimental realization of different launcher stage flight scenarios (under 1g conditions). Equipped with model cryogenic propellant tanks (typical scale factor of 1:4 to 1:5) dynamic fluid topology and propellant behaviour can be investigated during sloshing, filling and draining procedures. Fig. 1 shows a cryogenic tank demonstrator tank mounted to the hexapod experiment platform for large scale LN_2 sloshing tests.

In addition to LN_2 and LH_2, the Cryo-Lab further supports liquid methane (LCH_4) tests through its in-house liquefaction system and liquid oxygen (LOX) material compatibility tests.

Test Setup

For liquid-gas interface observations, a bath immersion cryostat holding up to 60 litres of LN_2 (Fig. 2, left panel) was equipped with a heater for bubble generation, top-/side-view cameras and the actual tomographic sensor setup. Two types of sensor arrangements were chosen: sensor rings aimed at the detection of bubbles passing through them, and bubble traps aimed at the 'trapping' and growth of larger bubbles not normally encountered in 1g conditions.

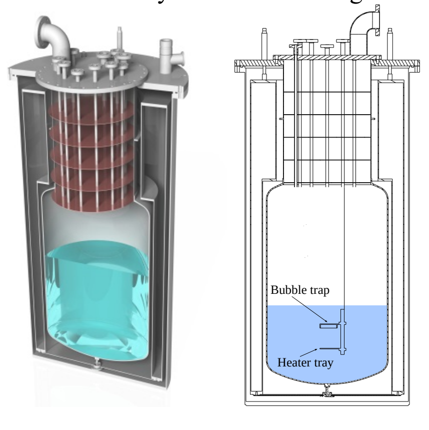

Fig. 2: Rendering of the bath cryostat used in the present work (left panel), with a schematic showing a bubble trap and heater mounted inside the cryostat (right panel).

A typical sensor bubble-trap setup is schematically shown in Fig. 2 (right panel) as an example, a component sizes and distances were adapted depending on the measurement technology under investigation.

For the fibre-optic temperature sensor validation, bath immersion cryostats holding up to 25 litres of LH_2 were equipped with conventional resistance thermometers for comparison, calibration and validation purposes.

V. ELECTRICAL CAPACITANCE TOMOGRAPHY

Electrical capacitance tomography (ECT) is a non-intrusive and non-invasive tomographic technology that is currently used to monitor gas/liquid distributions in process engineering or gas/solid flows. ECT can also be applied to locate individual bubbles or to measure phase fraction distributions[1]. Usually an ECT sensor consists of eight to twelve electrodes arranged in a circle and facing each other. Between every pair of electrodes the capacitance is measured. Since these capacitances depend on the permittivity distribution of the region between the electrodes, it is possible to draw conclusions from the capacitance measurements on the material located in the area the electrodes enclose. Owing to the fact that only currents in the range of 10^{-6} A are needed for the measurements, the heat input into the volume under test, i.e. a cryogenic tank, is negligible[2].

We have built two ECT systems with the aim to detect the appearance of gaseous bubbles in liquid nitrogen and to monitor the onset of boiling on a surface under cryogenic conditions: a ring comprising 16 electrodes and a so -called bubble trap used to provide a steady gaseous volume inside a liquid nitrogen reservoir. The changes in capacitance induced by the appearance of bubbles in the liquid are small compared to water because of the small relative permittivity of liquid nitrogen (Table 1).

	nitrogen	water
ε_{liquid}	1.4	55.4
$\varepsilon_{gaseous}$	1.0	1.0

Table 1: Dielectric constants of nitrogen and water at their boiling point (ε_{liquid}) and in their gaseous phase ($\varepsilon_{gaseous}$)[3,4].

Experiments

First experiments were conducted in a cryostat filled with liquid nitrogen (LN_2) at the DLR Cryo-Lab. The geometries of both the ring and the bubble trap have been custom-designed to fit the inner tank of the cryostat. As can be seen in Fig. 3, the bubble trap consists of five electrodes and two windows to render the observation of the filling level inside the trap possible. When bubbles generated by a heater below the trap ascend in the liquid, they are collected in the trap and merge to one big bubble, thereby lowering the filling level of LN_2 inside the trap.

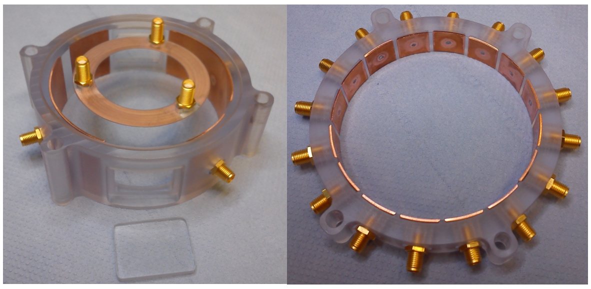

Fig. 3: Hardware realization: Bubble trap (left) and ring with copper electrodes (right), both made out of polycarbonate.

Figure 4 shows how the capacitance between opposing electrodes embedded into the wall of the trap changes with the amount of liquid nitrogen inside the trap. The capacitance is normalized to the range between minimum and maximum peak. Also depicted are two snapshots from the movie taken during the filling process. The camera looked through one of the windows in the bubble-trap wall and the window was marked with a cross to indicate the filling level. By this method, it was possible to obtain the correlation between filling level and measured capacitance.

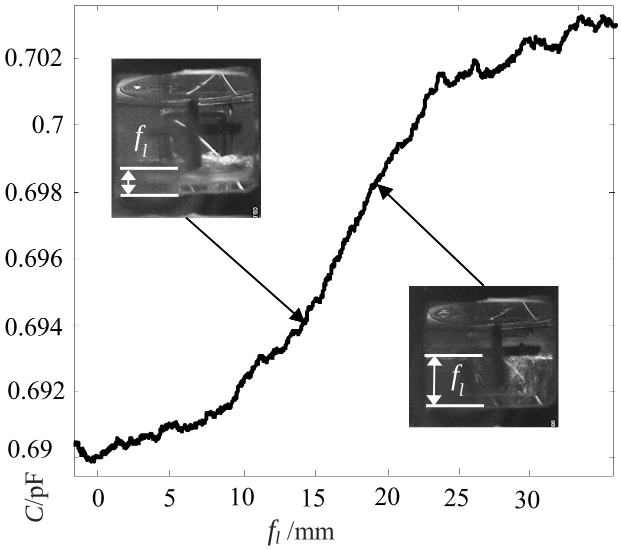

Fig. 4: Result of measurement of capacitance between two electrodes of the bubble trap during a decrease of the filling level f_l inside the trap from full to empty.

To detect small bubbles or a stream of bubbles ascending from the heater near the tank bottom, the electrode ring was used. For an ECT image reconstruction, the capacitances of all 120 possible electrode pairs were measured. By way of an example, a typical capacitance-versus-time curve is shown in Figure 5(─) for the case of two electrodes facing each other. As the heater power (---) is increased, the volume of the resulting bubble stream also increases. Consequently, the mean gas fraction grows whereas the capacitance falls. The gas fraction additionally depends on the pressure inside the liquid. This affects the slope of the capacitance curve and leads to capacitance changes even in time intervals with constant power. Note that the absolute pressure ranges from 1.03 bar to 1.2 bar.

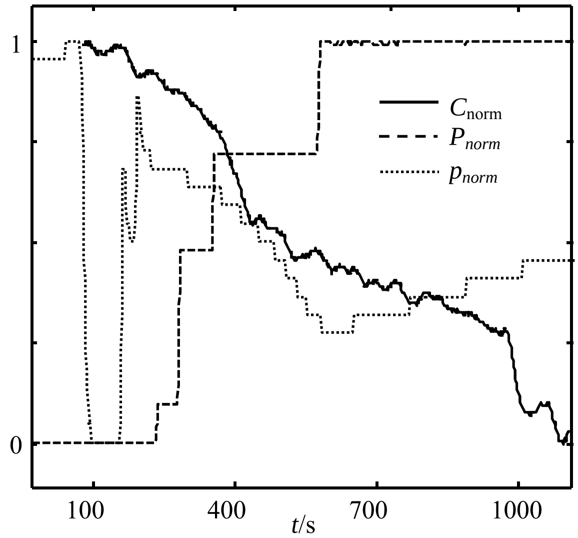

Fig. 5: Sample measurement result. Dashed line (---): power input P_{norm} to the foil heater. Solid line (─): capacitance C_{norm} between electrodes 1 and 9 (opposing pair). Dotted line (…): pressure p_{norm} inside the cryostat. All curves have been normalized to the interval [0,1].

VI. ULTRASOUND TOMOGRAPHY

Ultrasound tomography is widely used as non-invasive and non-intrusive imaging system in medical applications and is set to gain importance for real-time monitoring of actual processes in many industrial applications[5].

The system reported in this paper presents an ultrasound transmission tomography system for imaging of gas and cryogenic liquid flow - especially rising gas bubbles in liquid - and the gas/liquid level.

Principle

The ultrasound transmission measurement is based on the interaction of ultrasound waves at the interface of different media with different acoustic properties.

An ultrasound pressure wave is generated in the liquid by excitation of a piezoelectric transducer. The amount of transmitted energy is determined by the acoustic impedance mismatch between two components of the medium, e.g. gas and liquid[6]. In case the ultrasound wave is passing through a liquid nitrogen (LN_2) and gaseous nitrogen (N_2) boundary, over 99.89 % of the acoustic signal is reflected[7]. The change of the transmitted acoustic signal amplitude caused by the acoustic impedance mismatch provides the basis for the detection of rising gas bubbles in liquid and gas/liquid level sensing.

Measurement method

For the ultrasound transmission measurement a sensor ring and a bubble trap are manufactured utilizing polycarbonate (PC) material in a circular geometry (Fig. 6).

Fig. 6: Bubble trap (left) and sensor ring (right) equipped with piezoelectric transducers.

A sensor ring is used in a fan-shaped beam sensor geometry for gas bubble detection in LN_2. In total, 32 piezoelectric transducers are equidistantly positioned around a container ring at the same level. The transmitting and receiving of ultrasound waves are controlled by a multiplexing unit. That enables the generation of multiple projection data by switching individual piezoelectric transducers from receiving mode into transmitting mode and the reverse.

Ultrasound transmission tomography is a binary measurement system. By reconstructing the image via back projection algorithm it is especially suitable for size and location monitoring of rising gaseous nitrogen bubbles[8].

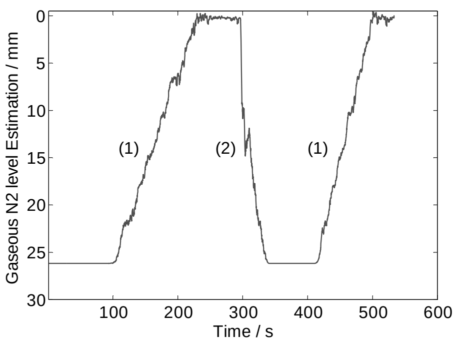

Fig. 7: Estimated gas level from the transmission measurement during linear emptying (1) and filling procedure (2) the trap with N2.

A bubble trap is positioned above the sensor ring to collect the rising gas bubbles. The bubble trap is equipped with 16 piezoelectric transducers to measure the liquid/gas level. At one side, 8 transmitting transducers are positioned at different levels. On the opposite side, every transmitter has a corresponding receiving transducer at the same level. By receiving an acoustic signal it is possible to sense the gaseous nitrogen level in liquid nitrogen (Fig. 7).

The combination of both systems enables the gas and liquid flow measurement in a cryostat.

Engineering challenges

The electrical connection and the mechanical coupling of piezoelectric transducers under cryogenic temperature and high vacuum conditions determine special requirements for the measurement system. These challenges have been solved by a special encapsulation design for the transducers; there are no parts in the system which are affected by degradation of solder points or glue bondings.

The only non-influenceable factor is the decreasing oscillation displacement of the piezoelectric transducers at low temperatures. In LN_2 at 77 K transducers achieve only 70 % and in LH_2 at 20 K only 30 % of the displacement at room temperature. However, even at LN_2 the transmitted signal has an amplitude of a few hundreds of millivolts, a signal strength sufficient for accurate evaluation[9].

VI. FIBRE-OPTIC TECHNOLOGIES IN LIQUID NITROGEN AND HYDROGEN

Optical fibres can serve as sensors for temperature, pressure, strain, chemical composition, and further derived physical quantities. Using the whole length of a fibre as sensing element, distributed measurements are enabled (as opposed to point-wise measurements of other state-of-the-art technologies), ideally suited for recording temperature fields in gas and liquid phases. In a cryogenic environment, further advantages of optical fibres include a potentially decreased heat flux and chemical inertness (relevant in hydrogen experimentation).

Bundled optical fibres can be employed as light guides or as image guides, the latter extending the field-of-view of a laboratory camera into a cryogenic experiment volume.

Fibre-Optic Temperature Measurements in LH_2

Validation experiments of optical fibres for temperature measurements were conducted in the DLR Cryo-Lab in both liquid nitrogen (77 K) and liquid hydrogen (20 K).

Figure 8 shows a temperature profile in a bath cryostat as measured with a coated SMF-28 optical fibre, vertically suspended through a stratified hydrogen gas phase, ranging in temperature from 140 K to 20 K, in contact with liquid hydrogen in its lowest most segment.

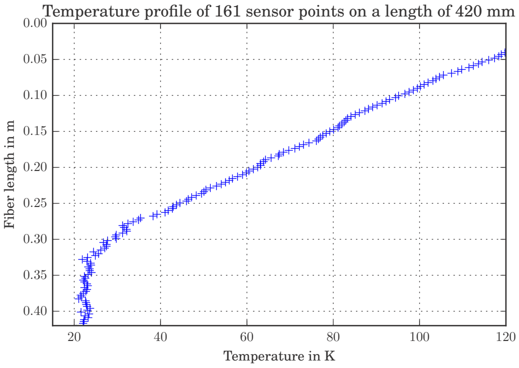

Fig. 8: Vertical temperature profile in liquid and gaseous hydrogen inside a cryostat, as measured with an optical fibre.

The temperature profile is made up of 161 sensor segments along 420 mm of fibre length, leading to a 'quasi-continuous' 1D profile recording.

For optical fibres, the present test in liquid hydrogen (and liquid nitrogen) is of prime importance for the assessment of temporal and spatial temperature field resolution, the material compatibility between cryogenic liquid and the fibre coating, and the fibre sensor performance in a realistic environment.

Measurement Principle

Temperature-induced changes in the Rayleigh-backscatter signal of the fibre under test (FUT) were interrogated using Optical Frequency Domain Reflectometry (OFDR)[10]. As temperature is lowered (or increased), the characteristic backscatter frequency profile of the FUT (its 'fingerprint', caused by small refractive index variations due to material imperfections) undergoes a shift. The shift is owing to the temperature-dependence of the fibre refractive index (thermo-optic effect) and the contraction/expansion of the fibre together with its coating.

Engineering Challenges

Since both the refractive index change and thermal expansion exhibit a strongly non-linear behaviour as temperatures approach the cryogenic domain, thorough calibration of frequency shift as a function of temperature is required. This non-linearity is such that the temperature sensitivity of the refractive index and the fibre/coating coefficient of thermal expansion both decrease with temperature, rendering temperature measurements especially in LH_2 more difficult.

In this work, platinum resistance thermometers were used for calibration of the mentioned non-linearity in LH_2, deriving a relation between frequency shift and temperature specific for each fibre and its coating material. Since precise material composition, coating thickness, and application method may vary between fibres, an individual calibration is required for each fibre type.

The Rayleigh-backscatter method achieves temporal resolution in the millisecond domain and spatial resolutions in the mm domain, both of which need to be traded-off against the signal-to-noise ratio (increased temporal and/or spatial resolution decreases the signal). This is of particular importance at cryogenic temperatures, where there is an additional signal decrease due to lower temperature sensitivity.

Fibre-Optic Bundles Tests in LN_2

A flexible fibre-optic bundle was tested for the observation of bubbles rising from a foil heater in LN_2. The bundle, acquired commercially off the shelf and not previously rated for cryogenic use, is made of ~10^5 individual fibres wound together, constituting an optically active area of 4x4 mm. The flexibility of the bundle means that within the confines of its bending radius, the field of view can be adjusted (while the bundle is at ambient temperatures and the fibres not brittle) and insights not provided by cameras achieved.

For the purpose of the present test, the bundle was mounted in the bath cryostat and was exposed to temperatures as low as 100 K in the nitrogen gas phase above the liquid nitrogen.

Figure 9 displays a photo taken through the fibre-optic bundle, showing the heater submerged in liquid nitrogen blurred due to nitrogen convection. The inset magnifies the bundle structure, showing square blocks of 10x10 fibres constituting the bundle.

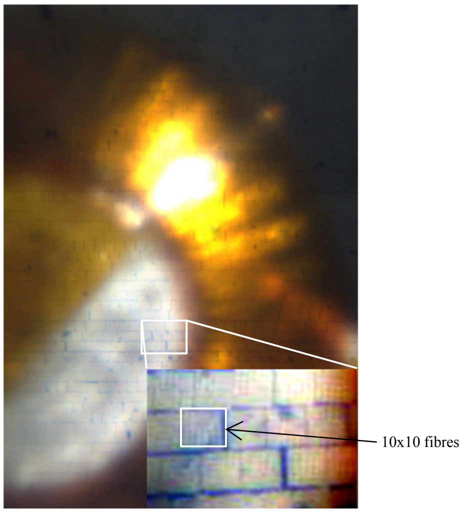

Fig. 9: View through a flexible optical fibre bundle into a cryostat, observing liquid nitrogen convection above a foil heater, with the magnification showing the square arrangement of single fibres.

VII. CONCLUSION AND OUTLOOK

Comprehensive sensor tests in LN_2 at 77 K and LH_2 at 20 K were carried out for a range of sensors and measurement devices, some of them being introduced to the cryogenic domain for the first time.

- For Electrical Capacitance Tomography, the conducted experiments show that despite the very small relative permittivity difference of $\Delta\varepsilon_r = 0.4$ between gaseous and liquid nitrogen the filling level and large-scale bubbles can be easily detected by a sensor system based on capacitance measurement. The measurement results also reveal the high sensitivity of such a system towards different densities of bubble streams. The materials used to build up the system all proved their applicability for operation under cryogenic conditions.
- For Ultrasound Tomography, the first tests in LN_2 demonstrate the functional capability of the bubble trap and the sensor ring in gas/liquid imaging. This ultrasound transmission measurement system especially designed for the monitoring and sensing of cryogenic liquids and gases allows the measurement of static and dynamic processes and is able to monitor the actual process. In future work, it is intended to test the system under realistic conditions in liquid hydrogen (LH_2) at 20 K.
- The performance of flexible fibre-optic image guides has been demonstrated for temperatures as low as 100 K.
- Quasi-continuous fibre-optic temperature measurements, featuring 161 sensor points along 420 mm of fibre, were carried out in LH_2, measuring a temperature profile between 20 K and 120 K. Tests of different fibre coating options and a thorough assessment of the relation between temporal resolution, spatial resolution and measurement accuracy are intended as next steps.

The conducted experiments demonstrated the need to carry out sensor tests in the relevant cryogenic liquid environment (LN_2, LH_2). Only this approach enables the assessment of real sensor performance and material compatibility in addition to low temperature resilience.

Finally, the potential of the sensors to aid the validation of CFD simulations has been shown and now needs to be followed-up by further investigations at lower temperatures (where applicable) and in additional spaceflight applications scenarios such as cryogenic liquid propellant tank sloshing.

ACKNOWLEDGEMENT

Parts of the presented work were carried out under contract from the European Space Agency (ESA), the support of which is gratefully acknowledged.

[1] C. G. Xie et al. "Electrical capacitance tomography for flow imaging: system model for development of image reconstruction algorithms and design of primary sensors", *Circuits, Devices and Systems, IEE Proceedings G, Vol. 139, No. 1, February 1992, pp. 89-98*

[2] M. S. Beck et al. "Principles and Industrial Applications of Electrical Capacitance Tomography", *Measurement and Control, Vol. 30, No. 7, September 1997, pp. 197–200*

[3] Uematsu, M., and E. U. Frank. "Static dielectric constant of water and steam." *Journal of Physical and Chemical Reference Data* 9.4, (1980), pp. 1291-1306.

[4] J.E. Jensen et al. "Selected cryogenic data Notebook – Volume II", *Brookhaven National Laboratory, August 1980*

[5] B.S. Hoyle, and L.A, Xu, "Ultrasonic Sensors," *in R.A. Williams and M.S. Beck, Process Tomography: Principles, Techniques and Applications, Oxford: Butterworth-Heinemann, pp. 119-149, 1995.*

[6] B.S. Hoyle, "Process Tomography Using Ultrasonic Sensors," *Journal Measurement Science Technology, vol. 7, pp. 272-280, 1996*.

[7] NDT Education, https://www.nde-ed.org/GeneralResources/MaterialProperties/UT/ut_matlprop_index.htm

[8] A. Plaskowski, M.S. Beck, R. Thron, and T. Dyakowski, "Imaging Industrial Flows: Applications of Electrical Process Tomography," *U.K.: IOP Publishing Ltd., 1995.*

[9] PI Ceramic, http://piceramic.com/piezo-technology/properties-piezo-actuators/temperature-dependence.html

[10] D. K Gifford, B. J. Soller, M. S. Wolfe, and M.E. Froggatt. "Distributed Fiber-Optic Temperature Sensing using Rayleigh Backscatter." *In ECOC 2005 Proceedings (pp. 2–3), 2000.*