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Metrological support for LNG custody transfer and transport fuel applications
ENG60 LNG

Report on the LN2 tests with the LDV standard (Task 1.4.3 WP1)

R.MAURY
A.STRZELECKI
Y.LEHOT
J.P. VALLET

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1. **Summary of the Join Research Program**

**Background**

Liquefied Natural Gas (LNG) is a strategic, and in the case of long distances, a more economical alternative for pipeline gas. It is also used to transport natural gas from and to locations where no pipeline infrastructure exists. After regasification of the liquid form, the natural gas is transported to the main users: power plants, industry and households. Recently the use of LNG as a cleaner transport fuel has been added to the list of important applications.

**Need for the project**

In comparison with other commodities like natural gas or gasoline the total uncertainty of measured energy is high for LNG and has been estimated to be up to 1%. The current lack of direct traceability to the SI also leads to the delayed introduction of new measurement methods in the LNG business. Therefore, a sound metrological framework is an indispensable element for the development of LNG as transport fuel, which is one of the pillars of the EU clean fuel strategy.

**Scientific and technical objectives**

The aims of the JRP are to further develop the metrological framework for LNG, to contribute to a reduction of the measurement uncertainty of LNG custody transfer by a factor two (starting from 1%) and to enable the development of LNG as a clean transport fuel.

Therefore, the JRP addresses the following objectives:

**WP1** will develop and validate novel and traceable calibration standards of LNG mass and volume flow for vehicle fuel dispensing and ship bunkering. A mid-scale LNG mass and volume flow facility up to 200 m³/h (90 tons/h) will be built and validated. This standard will be traceable to the previously developed primary flow standard. It will furthermore be cross-validated using a new Laser Doppler Velocimetry (LDV) based standard. From the results a new ISO standard will be drafted (as part of WP5) to pave the way for industry wide adoption of the LNG flow measurement technology.

**WP2** will develop and validate novel and improved methods for measuring LNG composition to address the online monitoring of the LNG quality and issues with sampling LNG. A LNG composition calibration system will be developed and integrated into the LNG flow facility. It will be cross-validated with a newly developed reference LNG liquefaction system. The latter will also be specially designed to validate Raman spectroscopy systems.

**WP3** will develop a publicly available method for the determination of the methane number, including a correlation of the methane number to the LNG composition, in support of the use of LNG as transport fuel. From the results a draft ISO standard will be created (as part of WP5) to harmonize the definition and measurement methods used by gas engine manufacturers worldwide.

**WP4** will validate and improve models for LNG density prediction and associated uncertainty evaluation. A new set of measurement data will be created with an uncertainty 5 times lower than existing data and an improved correlation between density and composition will be established. A cryogenic Speed of Sound (SoS) measurement system will also be developed to establish an improved correlation between SoS and density.

**WP5** is designed to maximize the impact for the JRP, by disseminating the results and by strengthening links to industrial stakeholders.

**WP6** describes the management of the JRP. The selected methods will ensure an effective and efficient project management.
Cesame Exadebit in the JRP:

A very promising alternative to the state-of-the-art static volume measurements is the dynamic principle of flow metering. WP1 addresses the great technological challenge of creating traceability for LNG flow meters that currently does not exist anywhere in the world. Providing a direct link to SI with a very small uncertainty and disseminating that link to a range of flows has never been done before and will be a unique achievement. The project will develop the know-how to ultimately provide traceability to the full range of LNG flows. The goal of this work package is the development of metrologically-sound traceability schemes for LNG flow metering.

A novel cryogenic flow metering technology, Laser Doppler Velocimetry (LDV), will be explored as promising an alternative to ultrasonic and Coriolis flow metering. LDV as a flow measurement technology has already been demonstrated in high pressure natural gas with an uncertainty of 0.1 – 0.2 % [1] but its extension to cryogenic temperatures is challenging and will be checked for its feasibility.

CESAME EXADEBIT has performed a feasibility study of LDV technology applied to LNG flow metering during the first LNG program (2011-2014). The study has been focused on the technological challenges and solutions for extending the LDV method to cryogenic temperatures, and on the estimation of the uncertainty that can be realistically achieved with such a system.

The previous report was based on air experiments in Poitiers. This report is dedicated to the experimental campaign conducted in cryogenic conditions with Nitrogen in the NIST facility.

2. Introduction

CESAME was looking for a cryogenic facility where uncertainties were known and controlled. We planned to perform tests in the National Institute of Standards and Technology (NIST) facility in Boulder, Colorado (USA) with the help of Dantec Dynamics to provide us a calibrated laser (July 2015).

The cryogenic Laser Doppler Velocimetry device has been tested over a range flow rates (from 9 to 41 m3/h) at a fixed temperature and pressure to determine its performance characteristics. All measurements reported herein are traceable to national standards and underlying NIST calibration and Measurement Capability is included in the Key Comparison Database (Appendix C) of the “Bureau International des Poids et Mesures”.

3. Description of the DN80 Cryogenic LDV Measurement Package

The LDV measurement package is composed of three main sections: 1- the cryogenic seeding part, 2- the conditioning part (containing the convergent) with the measuring cross-section and 3the divergent.

The seeding part is equipped with an access for the seeding probes in cryogenic conditions, and with two windows for particles visualization (see figure 1). The conditioning part is provided with windows which allow passage of laser beams for measuring the velocity profile at the exit of the convergent. The downstream part of the Cryogenic LDV Measurement Package contains the divergent. These three parts are located inside a vacuum chamber to ensure thermal insulation.
The main characteristics of the cryogenic LDV system are described in more details in Strzelecki et al. [1]. There are briefly reminded below:

- Internal diameter $D=80$ mm
- Throat diameter $D=40$ mm
- Beta ratio of the convergent $\frac{d}{D} = 0.5$
- Length $L=6D$
- Maximum operating pressure : 10 bar

4. **Velocity measurements by means of the Laser Doppler Velocimeter**

   The velocity profiles are measured by means of a Laser Doppler Velocimeter DANTEC (Figure 3) in the backscattering mode (Figure 2) with the following specifications:

   - Wavelength of the laser line = 532 nm green line of a frequency doubled Nd:YAG laser
   - Focal length = 160 mm
   - System configuration = backscattering mode
   - Data acquisition and signal processing = DANTEC BSA Flow Software
   - Traverse system controlled from the PC running BSA Flow Software for laser displacements
   - Size of the measurement volume: $l = 0.0496$ mm and $L = 0.4105$ mm
   - Interfringe spacing = 2.217 $\mu$m.

![Figure 1: Description of the simplified Cryogenic LDV Measurement Package and (b) 3D model horizontal cut view.](image)

![Figure 2: Backscatter configuration](image)
5. Experimental setup and test plan

The LDV package test was run on the NIST cryogenic flow measurement facility. This facility, shown schematically in figure 4, has a combined uncertainty in the measurement of the totalized mass of 0.17% (see Scott et al. [3]) and a combined uncertainty of 0.18% for the totalized volume flow (k=2). This uncertainty statement applies to measurements made within a flow range of 20 to 200 gallons per minute (75 to 750 L/m). This uncertainty differs from that stated in reference [3] since NIST have incorporated a newer equation of state for nitrogen (see Span et al. [4]), and the uncertainty in density for the new equation is 0.02% (k=2).

A rangeability test was run to determine the flowmeter performance over a range of flow rates and fixed temperature and pressure. The temperature was about 80K, the pressure range was about 5 bar. There were 5 separate flowrates selected which were repeated at least 3 times. During this experimental campaign, CESAME only tried to calculate volumic mass flow rate by using single point measurement in the jet centerline axis.
The test plan is reminded in the figure 5 below. Due to a short experimental campaign, CESAME mainly focused on the single point measurement over a range of Reynolds number from \(2^5\) to \(2^6\) and two seeding techniques (hotwire and helium bubbles injection).

<table>
<thead>
<tr>
<th>Run</th>
<th>Qm (kg/s)</th>
<th>Throat velocity (m/s)</th>
<th>Mach Throat</th>
<th>Re Col</th>
<th>Objectives</th>
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<td>9,2</td>
<td>0,03</td>
<td>2,00E+06</td>
<td>Centerline velocity</td>
</tr>
</tbody>
</table>

**Figure 5**: Test plan during cryogenic experimental campaign in NIST facility with the LDV package.

6. **Objectives**

During this campaign, CESAME has the possibility to confirm that the LDV package can operate in cryogenic conditions. It can also allow CESAME to validate technical choices and answer numerous hypothesis regarding the cryogenic conditions such as:

1. mechanical behavior in cryogenic conditions,
2. Vacuum level required to perform velocity measurement without icing on portholes,
3. Optical convergence of the beams with liquid nitrogen,
4. instrumentation permeability with cryogenic fluid,
5. Seeding.

7. **Single point measurement: results and discussion**

The laser beams convergence has been determined with accuracy by taking into account the length modification of the convergence beams due to nitrogen reflection indices. Convergence positioning (during experiments) have been controlled using a remoted camera mounted on one of optical access of the LDV package (on the top) since no one can be close to laser during experiments (safety procedure - class 4 laser). The laser system has not been moved in order to insure the convergence of the beams to the centerline axis close to the throat (\(x/D = 0.25\) approximatively). The experimental setup is visible in figure 6.

**Figure 6**: Experimental setup for LDV measurement in the NIST facility.
The main goal of these tests was to determine the correlation function \( \mathcal{A}(Re) \) in cryogenic conditions (same procedure realized during air based experiments). During these experiments, the upstream pressure has been fixed around 5 bar and the velocity has been increased from 2 to 9 m/s resulting in a Reynolds number based on the throat diameter from \( 4.3 \times 10^5 \) to \( 2.0 \times 10^6 \). Each mass flow rate have been repeated at least 3 times to access standard deviation in the laser results. A trigger signal was sent from the NIST acquisition system to our laser/sensors acquisition system to provide relevant set of data to perform the measurements and calculations.

CESAME (as a first attempt) has applied the correlation function determined during the air based campaign in Poitiers. It is clear that the fluid properties modification (from air to cryogenic liquid) will play an important role in the definition of this correlation function (reduction of viscosity for example). Nevertheless, this NIST campaign has provided a new correlation function for cryogenic conditions that CESAME will test in another cryogenic tests soon. CESAME has also taken into account the temperature constraints on the flowmeter body to calculate the velocity from the NIST sensors. Indeed, the reduction of the throat diameter due to cryogenic temperature affects the accuracy and has to be considered. The paper of Thermeau [5] presents the length modification \( \Delta l/l \) as a function of temperature in Kelvin (see figure 7). In our case, the \( \Delta T \) is 213K resulting in a length modification around 0.27% on the throat diameter.

**Figure 7:** Modification of the throat diameter due to cryogenic temperature from Thermeau [5].

The figure 8 presents the results of the bias in velocity between the standard facility and the LDV package. The extended uncertainty of the facility have been added to the results.

**Figure 8:** Velocity difference (with air based correlation function) between NIST standard facility and LDV package.
As a general comment, the trend observed during the air experiments are conserved in cryogenic conditions since at low Reynolds number, the correlation function plays a higher role. The Reynolds number increasing leads to a reduction of the momentum thickness in the shear region. The figure above shows that the comparison of the velocity between the standard facility and the LDV package is comprised between: -0.3% and 0.3% with 0.18% of extended uncertainty. As a fist attempt in cryogenic conditions, these results are really promising. CESAME wants to investigate further by having another experimental campaign during which, the correlation function defined in cryogenic conditions will be used to reduce the bias observed in the figure 8.

8. Feedback on objectives

During this tests, a lot of subjects needed to be investigated (as reminded in section 6). CESAME knowledge on cryogenic conditions has been significantly improved during this campaign. The explanation for each topic is given below:

1. Mechanical behavior in cryogenic conditions: our LDV package has operated correctly during all campaign. No internal leakage has been detected and the thermal constraints of the body part was correctly handled by all the seals / O rings used in our system.

2. Vacuum level required to perform velocity measurement without icing on portholes: the vacuum system has operated efficiently during the runs with a vacuum level around 1x10^{-4} mPa. It was enough to provide decent vacuum level to avoid icing on the portholes.

3. Optical convergence of the beams with liquid nitrogen: the optical path has been theoretically calculated and it appears that it is relevant with what we saw during testing. The convergence of the beams allows us to perform LDV measurements with high accuracy level.

4. Instrumentation permeability with cryogenic fluid: no leakage detected during tests.

5. Seeding: Both natural seeding and external forcing seeding have been tested in the NIST facility. When external seeding was required, two technologies have been used (hotwire and helium bubbles injection). From what has been understood, CESAME want to build a new injector to provide better seeding quality in a near future (partial validation).
9. Photography of the NIST experiments
10. Conclusions & Perspectives

CESAME has already demonstrated the flow measurement accuracy with air based experiments (mean and RMS velocity profile) and the capability of the system to perform accurate measurement in cryogenic conditions (see Task D1.4.2).

This LDV method allows to provide the single point measurement velocity on the centerline axis of the jet over a large range of Reynolds number ($5 \times 10^4$ to $2 \times 10^6$). This method can be used to calibrate on-site flowmeters (Coriolis, ultrasonic flowmeters...) which operate with cryogenic conditions. This technique has several advantages since it is much quicker and optical adjustments are much easier to realize. The flowmeters will be calibrated with real experimental conditions (temperature, pressure, fluid properties and large range of mass flow rate and Reynolds number).

As a first attempt on cryogenic conditions, the results are really promising and CESAME wants to investigate further the LDV technology as a credible alternative to realize on-site calibration of cryogenic flowmeters. This LDV package can be also used to provide aerodynamics features of the flow (installation effects or boundary layers profiles for example).

In a near future, CESAME want to perform LNG measurement in Montoir de Bretagne with the collaboration of ENGIE. A first test has already be realized showing the potential and capability of our concept.
11. References


