Laser Doppler Velocimetry as a primary standard for cryogenic flow meters

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Abstract

A very promising alternative to the state-of-the-art static volume measurements for Liquid Natural Gas (LNG) custody transfer processes is the dynamic principle of flow metering. In the frame of the first (2010-2013) & second (2014-2017) Joint Project Research named "Metrological support for LNG custody transfer and transport fuel applications", Cesame Exadebit explored a novel cryogenic flow metering technology using Laser Doppler Velocimetry (LDV) as an alternative to ultrasonic and Coriolis flow metering. Cesame tries to develop this technique as a primary standard for cryogenic flow meters. Indeed, cryogenic flow meters are currently calibrated at ambient temperature with water. Results are then extrapolated to be in the Reynolds number range of real application. The LDV concept can provides on line calibration of cryogenic flow meters with real conditions (temperature, pressure, piping and real flow disturbances).

This present paper is organized as follows. In the first section, the technical solution to perform a cryogenic measurement with LDV system (optical windows, vacuum insulation, seeding...) are presented. The second chapter is devoted to the assessment of the shear layer dependence on the mass flow ($\dot{m}(u, \delta_\omega, R_e)$) with a simplified measurement package by means of experiments conducted with air based. The third chapter presents experiments that have been realized in cryogenic conditions in the National Institute of Standard and Technology (NIST) in Boulder, Colorado using Liquid Nitrogen. Finally, section IV gives some conclusions and perspectives for future work.

1. Introduction

Liquefied Natural Gas is a strategic, and in the case of long distances, more economical alternative for the pipeline gas. Indeed, there is an increase of the global market regarding both pipeline and in the form of LNG transfer over the past decades. The figure 1 (based on the data from the BP *Statistical Review of World Energy*) shows that the amount of traded as LNG has tended to grow more rapidly that the pipeline configuration.

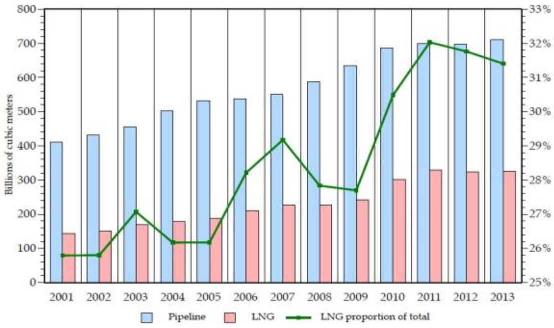

Figure 1: International pipeline and LNG Imports (from BP Statistical review)

The measurement of this energy has to be efficient and accurate and the related uncertainties have to be extremely low regarding the constant trading between suppliers. The objectives of LNG custody transfer operations are to measure the quantity of energy loaded from production facilities into an LNG carrier, or unloaded from an LNG carrier to a receiving terminal. To accomplish this, a number of elements must be measured and calculated: LNG volume (in m^3), LNG density (in kg/m^2), LNG gross calorific value (in *MMBTU/kg*), the energy of the gas displaced during the transfer of LNG in MMBTU and finally (if applicable) the energy of the gas consumed in the LNG carrier's engine room (see GIIGNL 2015 – [1]). The energy equation can be written as follow:

$$E = (V_{LNG} + D_{LNG} + GV\ V_{LNG} + E_{gasdisplaced} + E_{gastoER}). \quad (1)$$

LNG volume quantity is being measured on-ship using tank level measurement systems in combination with tank calibration tables. 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% (see Kerkhof [2]). When the ship suffers from wave motion (off shore), the measurement becomes even more difficult. The tank calibration poses an additional challenge.

The aim of the related JRP is to further develop the metrological framework for LNG, both for small and large scale applications. This will lead to a significant reduction of uncertainties in the determination of transferred energy in LNG custody transfer processes. Cesame Exadebit has been involved in the development and validation of novel and traceable calibration standards of LNG mass and volume flow for vehicle fuel dispensing and ship bunkering. To measure LNG volume, we studied the capability of a flow measurement system using a Laser Doppler Velocimetry (see Strzelecki *et al*. [3]). The LDV system may provide an alternative traceability route for LNG volume flowmeters. It can also be used as a non-intrusive instrument to perform flow profiles measurements in a cryogenic medium.

LDV as a flow measurement technology has already been demonstrated under high pressure with natural gas (5.5 *MPa*) with an uncertainty of 0.22% (see Mickan *et al.* [4]) but its extension to cryogenic temperatures is really challenging because:

1. The measurement of a velocity component in LNG by means of LDV requires the introduction into the fluid through one optical path of two laser beams which intersect to form the measurement volume. There are two features that have to be taken into account: the size of the volume measurement has to be calculated in order to capture the main aerodynamic features of the flow and most importantly, the fluid temperature is around -166°C whereas the flow measurement system is at ambient temperature. We must prevent icing on the optical path to perform an accurate velocity measurement.
2. The LDV measurement requires the presence of micron-size tracers in the fluid. In the absence of natural micron-size tracers, it is mandatory to provide a clean seeding system that does not contaminate the fluid.
3. The objective is to measure instantaneous LNG flow rate with an accuracy of 0.2% with traceability of the measurement

The study focuses on the technological challenges and solutions for extending the LDV method to cryogenic temperatures by a two-step approaches. First, the air based experiments realized in Poitiers are presented then the liquid nitrogen experiments on the traceable facility (NIST, Colorado) are debated.

2. Experimental setup and LDV package description

2.1 Description of Cesame reference facility for flowrate measurements

The pressurized calibration facility for medium and high flowrates at Cesame Exadebit can generate flowrates from 8 m^3/h to 80000 m^3/h (normal conditions). A set of twelve Venturi nozzles (nominal flowrate: 1.5 to 1000 $m3.h^{-1}.bar^{-1}$) operating in sonic conditions is used for the determination of the standard mass flowrate. The test pressure range is from 1 bar up to 45 bar (absolute). Compressed dry air stored in a 110 m^3 vessel under 200 *bar* (absolute) is used as the test fluid. The air coming from the storage vessel goes through the valves and the heating control system. This one adjusts the suitable temperature and pressure upstream the nozzles automatically. This configuration allows a comparison between the reference and tested device mass flows. The pressure and the temperature can be measured at the level of the meter in test in order to determine the volume flowrate going through. The real gas effects are taken into account by applying compressibility factor corrections to the thermodynamic conditions where the measurement is taken. These nozzles are traceable to National Standards by mean of a (P, V, T, time) method.

2.2 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 3 the 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 2). 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.

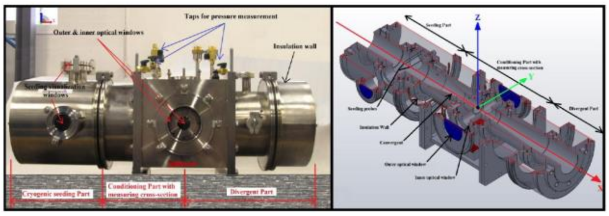

Figure 2: (a) Description of the simplified Cryogenic LDV Measurement Package and (b) 3D model horizontal cut view.

The main characteristics of the cryogenic LDV system are described in more details in Strzelecki *et al.* [4]. There are briefly reminded below:

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

The seeding unit is equipped with an access for external seeding forcing (probes in cryogenic conditions) and with two portholes for particles visualization. Indeed, LDV requires micron-size particles injection to achieve velocity measurements (if particles are not naturally in the tested fluid). The choice of the seeding system is important regarding the measurement accuracy. Two alternative systems can be used:

1. Injection of micron-size bubbles upstream the LDV measurement volume by local boiling of LNG using small electrical current.
2. Injection of a small flow rate of gas or liquid to generate micron-size particles.

The LDV measurement unit consists of an optimized convergent for conditioning the cryogenic flow before measuring the local velocity at the throat section by means of the LDV. Indeed, the shape of this convergent standardizes the main stream and provides a thin axial velocity gradient at the nozzle exit.

To process the LDV measurement, it is necessary to introduce into the model a dual laser beams that intersect at the measurement volume. It must be moved across the throat section of the convergent to provide velocity profile. These laser beams are introduced through two specific portholes. The first one is an interface between the cryogenic liquid (-166°*C*, pressure < 10 *bar*) and the insulation vacuum chamber (pressure at 10^{-5} *Torr*). The figure 3 presents the sketch of the optical configuration with the laser beams.

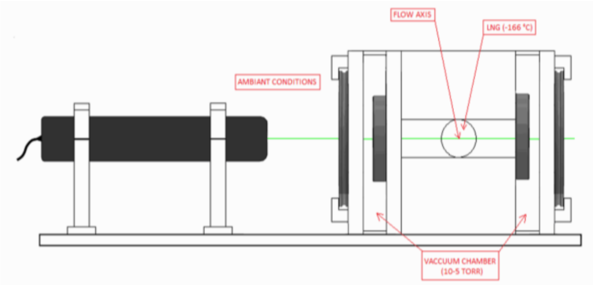

Figure 3: Optical configuration for the LDV package system (cross section view of the nozzle).

The second porthole is an interface between the insulation vacuum chamber and the ambient atmospheric conditions. These assembly needs a very accurate spatial positioning to maintain the parallelism which provides beams intersection in the perpendicular direction to the flow. In addition, these portholes have to withstand a large variation of temperature and pressure.

The velocity profiles are measured by means of a Laser Doppler Velocimeter from DANTEC in the backscattering mode (see figure 4) with the following specifications:

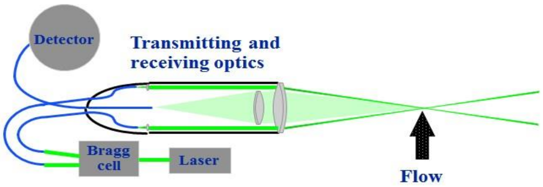

Figure 4: Backscattering configuration for flow measurement with the LDV package.

- Wavelength of the laser = 532 nm (green)
- Focal length = 160 mm
- System configuration = backscattering mode
- Measurement volume: l = 0.05 mm and L = 0.41 mm
- Interfringe spacing = 2.217 µm.

Further information regarding the LDV principle can be founded in Eder *et al.* [5].

3. Axial velocity measurement by LDV: measurement principle

The method to determine the volume flowrate from a local velocity (measured downstream of a throat) is presented in this section. The basic idea is to design a flow conditioner (convergent) that provides a symmetrical and flat velocity profile in order to assure a very repeatable and fast profile measurement. Once the boundary layers are analytically determined or directly measured, the flow rate measurement can be reduced to a single point measurement (centerline axial velocity measurement).

To be a primary standard, a theoretical framework needs to be develop to accurately determine the shear layer influence on the mass flow rate assessment (with a single point measurement in the centerline axis). As an example, if the velocity profile is a piston profile, the shear layer influence is negligible whereas in case of channel flow or free jet, the Reynolds stresses modify significantly the velocity magnitude over the diameter.

Cesame Exadebit is currently working toward this direction to propose this equipment as a primary standard for cryogenic flow meter. It is a challenging objective and Cesame needs to continue its journey to define the best theoretical approach to achieve this objective. In the meantime, the shear layer influence can also be determined experimentally by using a comparison with another standard. The LDV package is then a secondary standard in this case. In the following chapters of this paper, this approach will be presented.

The volume flowrate is obtained by measuring the mean velocity ($\bar{V}$) at the throat (if the velocity gradient has a small impact on the average flowrate). The governing equation can be written as equation 2:

$$Q_v = \pi R^2 \bar{V} \qquad (2)$$

For a given Reynolds number (Re), the output velocity is given by the relation 3:

$$\bar{V} = \frac{4Q_v}{\pi d^2} \qquad (3)$$

Furthermore, the ratio between the velocity on the axis V_{axis} (measured by the LDV system) and the output of the mean velocity $\bar{V}$ is a constant function of the Reynolds number based on the throat diameter d:

$$\frac{V_{axis}}{\bar{V}} = A(R_e) \qquad (4)$$

where

$$Re_d = \frac{\bar{V} d \rho}{\mu} = \frac{4Q_m}{\pi \mu d} \qquad (5)$$

These relations allow the calculation of the volume flowrate from the axial velocity measured at one point downstream the throat on the centerline axis. It can be written as follow:

$$Q_v = \pi r^2 \bar{V} = \pi r^2 \frac{V_{axis}}{A(Re_d)} \qquad (6)$$

To implement this method, it is mandatory to establish a correlation function between the volume flowrate and the local velocity measured as a function of the Reynolds number. The key parameter in this situation is the momentum thickness of the shear layer (δ_ω)

4. Experimental campaign: Air based experiments

4.1) Test matrix

During these tests, the Reynolds number has been increased from 6E^{+4} to 1.5E^{+6}. The table 1 shows the nominal conditions:

Table 1: Measurement conditions during experimental campaign

Upstream pressure	Nominal Velocity	Reynolds number	Mass flowrate
P (bar)	V (m/s)	Re_D	Q_m ($kg.s^{-1}$)
2	11.3	5.95E+4	0.033
	21.4	1.13E+5	0.064
	59.7	3.12E+5	0.176
5	10.8	1.44E+5	0.081
	21.1	2.81E+5	0.159
	58.8	7.61E+5	0.432
10	10.5	2.78E+5	0.158
	20.5	5.40E+5	0.306
	58.5	1.56E+6	0.862

4.2) Single point measurement in the irrotational zone (jet centerline axis)

The single point measurement has the main advantage to be quick and continuous. It is more convenient for industrial partners since this concept will directly be mounted on site with their real experimental conditions. The flow meter will calibrate other kind of measurement system which are currently calibrated with water (Coriolis or ultrasonic meter over a slight range of mass flow rate). This concept does not have technical limitation regarding the range of mass flow on-site (adjustment on pipe size might have to be done).

The goal of this experimental campaign is do one-point measurement to determine the correlation function A for a large range of Reynolds Number (with air). The single point measurement is taken in the potential core which is quasi irrotational.

During these experiments, a turbine has been mounted downstream the flowmeter in order to calculate the complete mass flow rate. Indeed, the reference mass flow is given by the sonic nozzle but it does not take into account the seeding amount of fluid added into the pipe. A piston flowmeter is also mounted on the seeding pipe to get information regarding the seeding mass flow. The sum of sonic nozzles mass flow and seeding mass flow (thanks to piston) should be equal to the turbine mass flow downstream the mass flow meter. Both of this equipment have been calibrated on the test bench before and after the experimental campaign with an extended uncertainty of (0.25%).

The Reynolds number is increased from 1.4E^{+5} to 1.5E^{+6}. The correlation function is defined in this range of Re$_D$ due to facility limitation. The upstream pressure has been raised from 5 up to 10 bar to reach the highest Reynolds number. The results of the campaign are summarized in the table 2 below. Physical parameters such as pressure, mass flow of the standard facility and our flowmeter are also reminded:

Table 2: Synthesis of the single point measurement with air based experiments in Poitiers.

Re$_D$	Q_v stdd m^3/h	P bar	$Q_{v\ LDV}$ m^3/h	V m/s	V_{axis} m/s	V_{axis}/V
1.44E+5	45.0	5	48.9	10.8	11.2	1.034
2.81E+5	91.7	5	95.8	21.1	21.7	1.026
4.14E+5	136.1	5	140.9	31.1	31.7	1.021
5.41E+5	182.0	5	187.2	41.3	42.0	1.018
7.94E+5	135.5	10	138.8	30.6	31.1	1.017
1.06E+6	181.3	10	185.0	40.8	41.2	1.011
1.52E+6	258.9	10	265.4	58.5	59.2	1.012

As reminded earlier, the direct comparison of the mass flow of sonic nozzles and LDV package cannot be done since the seeding is not taking into account with the standard facility. However, we can determine the mean axial velocity from the turbine mass flow. It is then possible to compare the direct single point velocity measurement with the latter quantity. The figure 9 shows the evolution of the correlation function (A) regarding Reynolds number increasing.

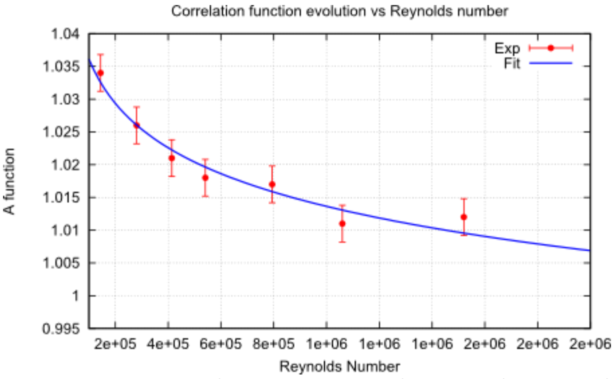

Figure 9: Correlation function evaluation for a specific range of Reynolds number (air measurement) with extended uncertainties from calibration.

The figure shows that the slope of the fit is monotonous and looks to be logarithmic. The Y error bars are the extended uncertainty obtained during turbine calibration. The figure also presents that the correlation function influence decreases when the Reynolds number increases. Indeed, the momentum thickness (δω) is significantly reduced. An analytical function has been determined by iteration and its expression is reminded below:

$$y = a + b.log(x) \qquad (7)$$

The single point measurement in air provides a database which allows to determine a correlation function to accurately determine the mass flow volume rate over a range of Reynolds number from $1E^5$ to $1.5E^6$. This measurement system offers unique advantages such as:

1. On site calibration of industrial flowmeter which are daily operating,
2. real test conditions (temperature, pressure and fluids properties),
3. no limitation in terms of mass flow rate (piping needs to be adjusted),
4. continuous velocity measurements with the same accuracy during transition (to reach the target velocity for example).

Cesame Exadebit needs to get confirmation that the trends observed with air measurements are still relevant with a cryogenic condition. Low temperature concerns are important and Cesame Exadebit has to verify numerous assumptions made for LDV package design. The next section is devoted to this matter.

4. Experimental campaign: Nitrogen based experiments

4.1) Experimental setup and test plan

The LDV package test was run on the NIST cryogenic flow measurement facility. This facility has a combined uncertainty in the measurement of 0.18% for the totalized volume flow (k=2) (see Scott *et al.* [6]). This uncertainty statement applies to measurements made within a flow range of 75 to 750 *L/mn*. NIST have incorporated a newer equation of state for nitrogen (see Span *et al.* [7]), 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 80*K*, 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 Exadebit only tried to calculate mass flow volume rate by using single point measurement in the jet centerline axis. The test plan is reminded in the table 2 below.

Table 2: Test plan during cryogenic experimental campaign in NIST facility with the LDV package.

Run	Qm (kg/s)	Throat velocity (m/s)	Mach Throat	Re Col
1	2,00	2,0	0,01	4,36E+05
2	2,46	2,5	0,01	5,37E+05
3	3,55	3,5	0,01	7,73E+05
4	4,91	4,9	0,01	1,07E+06
5	7,11	7,1	0,02	1,55E+06
6	9,17	9,2	0,03	2,00E+06

4.2) Objectives of the Nitrogen campaign

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 behaviour 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.

4.2) 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 converge of the beams to the centerline axis close to the throat (x/D = 0.25 approximatively). The experimental setup is visible in figure 10:


(a) Installation on the bench test (b) Laser running during tests

Figure 10: Experimental setup for LDV measurement in the NIST facility.

The main goal of these tests was to determine the correlation function (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 $4.3E^5$ to $2.0E^6$. Each mass flow rate has 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 has applied the correlation function determined during the air based campaign in Poitiers. The Reynolds number is the similitude criterion. Even if, there is a fluid properties modification (from air to cryogenic liquid), the correlation is not expected to be highly modified. Nevertheless, this NIST campaign has provided a new correlation function for cryogenic conditions that Cesame will test 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 [8] presents the length modification (Δl/l) as a function of temperature in Kelvin. In our case, the ΔT is 213K resulting in a length modification around 0.27% on the diameter.

The figure 11 presents the results of the bias in velocity between the standard facility and the LDV package. The extended uncertainty of the facility has been added to the results.

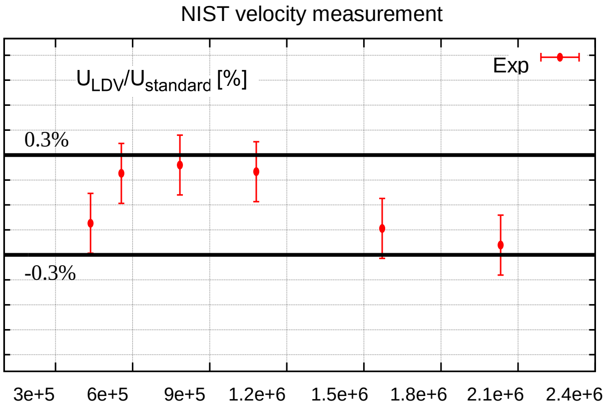

Figure 11: Velocity difference (with air based correlation function) between NIST standard facility and LDV package.

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 11.

4.2) Feedback on previous objectives:

During this tests, a lot of subjects needed to be investigated (as reminded in section 5.3). 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 1−4mPa. 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.

This method allows to provide the single point measurement velocity on the centerline axis of the jet over a large range of Reynolds number ($5E^4$ to $2E^6$). 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).

6. Conclusion and perspectives

In this paper the effectiveness of the LDV package developed by CESAME has been demonstrated. This technology can provide a large set of information regarding the aerodynamic events of the flow or can be used as a calibrating system for on-site cryogenic flow meters.
CESAME has demonstrated the flow measurement accuracy with air based experiments and the capability of the system to perform accurate measurement in cryogenic conditions.

In a near future, CESAME want to perform LNG measurement in a LNG terminal in collaboration with Reganosa (Spain) or Engie (France). An uncertainty budget in cryogenic condition is also expected soon.

7. References

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