LNG FLOWRATE MEASUREMENT USING LASER DOPPLER VELOCIMETRY

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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 Joint Project Research **"METROLOGY for LNG"**, **CESAME EXADEBIT** explored a novel cryogenic flow metering technology using Laser Doppler Velocimetry (LDV), as alternative to ultrasonic and Coriolis flow metering.

The study 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 measurement system to measure the LNG flowrate.

Introduction

The objective of LNG custody transfer operations is 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, LNG density, LNG gross calorific value and energy of the gas displaced during the transfer of LNG [1].

LNG quantity is being measured on-ship using tank level measurement systems in combination with tank calibration tables. The measurement of the liquid level of boiling LNG is much more complicated compared with water, oil or other non-cryogenic fluids. When the ship suffers from wave motion (off shore) the measurement becomes even more difficult. The tank calibration poses an additional challenge. The volumetric method is considered as the most precise method but has many drawbacks related to the completely different conditions (temperature, liquid density) during the calibration with water and the application with LNG. The resulting uncertainty claim of 0.3% is relatively high but in fact is believed to be rather optimistic [2]. There is currently no possibility to challenge the ship-based measurement result by using an on-shore alternative measurement system with flow meters.

The overall objective of the Joint Project Research **"METROLOGY for LNG"** is to contribute to a significant reduction of uncertainty in the determination of transferred energy in LNG custody transfer processes. The JPR consists of five technical work packages (**WP**), one creating impact and one management work package.

Custody transfer operations of Liquid Natural Gas (LNG) consist of measuring the energy of transferred LNG by measuring **volume, density and gross calorific value**.

A very promising alternative to the state-of-the-art static volume measurements is the dynamic principle of flow metering. **WP1** is addressing the great technological challenge of creating **traceability for LNG flow meters** that is currently not existing anywhere in the world.

In the frame of this JRP, **CESAME EXADEBIT** [3] explored a novel cryogenic flow metering technology using Laser Doppler Velocimetry (LDV), as promising 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 % [4] but its extension to cryogenic temperatures is challenging and has been checked for it's feasibility.

The study 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 measurement system to measure the LNG flowrate.

The paper presents the following points:

- Technical feasibility of a cryogenic LDV measurement system (seeding, optical access, etc.)
- Assessment of the volume flowrate measurement of LNG with a simplified measurement package by means of experiments conducted with air based on Reynolds Number similitude
- Synthesis of the feasibility study with conclusions about the obtainable uncertainty

Technical feasability

The first objective of this work was to study the technical feasibility of a cryogenic LDV Measurement system that allows to perform measurements in the LNG unloading conditions on a calibration facility of the CESAME laboratory with a substitution fluid (dry air).

As the NIST laboratory (USA) [5] is equipped with test loop in liquid nitrogen (-196 °C), we decided to study a cryogenic LDV measurement system that also allows us to perform measurements with this fluid.

Constraints provided by unloading of LNG are [3]:
- Maximum pipe diameter = 900 mm
- Maximum flow rate = 10000 m^3/h
- Maximum absolute pressure = 10 bar
- Maximum velocity of the fluid = 10 m/s

Constraints on the NIST test loop in Liquid Nitrogen [5]:
- Pipe diameter D = 80 mm
- Throat diameter d to be determined
- Maximum flow rate = 42 m^3/h
- Maximum pressure = 10 bar

The cryogenic LDV measurement system (Figure 1) consists of a LDV Measurement Unit and a Seeding Unit [5].

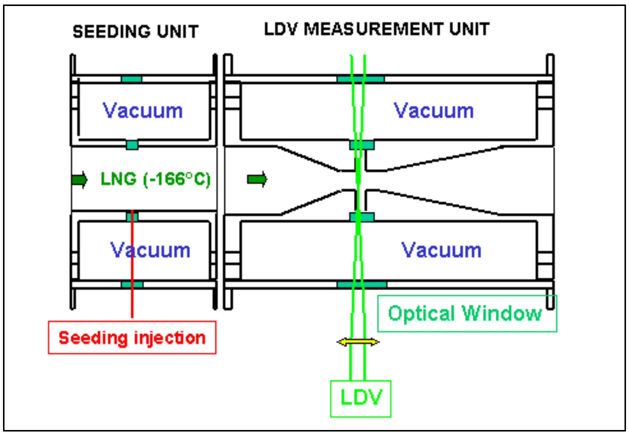

Fig. 1: Schematic Cryogenic Measurement system

The measurement LDV Unit consists of a convergent optimized for conditioning the cryogenic flow before measuring the local velocity at the throat section by means of the LDV. This velocity measurement allows the deduction of the volume flow rate of LNG.

To process the LDV measurement, it is necessary to introduce into the model two laser beams that intersect at a measurement volume that must be moved across the throat section of the convergent. These laser beams are introduced through two specific optical windows. The first one is an interface between the cryogenic liquid (LNG at T = -166 °C and pressure <10 bar) and the isolation vacuum chamber (-166 °C in Air <Temperature < 20 °C and pressure 10^{-5} to 10^{-6} Torr).

The second window is an interface between the isolation vacuum chamber and the ambient atmospheric conditions. The isolation chamber must also be equipped with a heating system to prevent pollution of the windows when the temperature of the model increases or decreases. To characterize the flow in the prototype by means of flow visualizations and LDV measurements, three optical accesses are provided. These windows need a very precise spatial positioning to conserve the optical characteristics of the laser beams in the measurement volume. In addition, these windows have to withstand great variation of temperature (Temperature from -190 °C to 30°C) and pressure (Pressure = 1 to 10 bar).

The seeding unit (Figure 1) permits the injection of micronic particles necessary for the LDV measurement. To control the seeding, two optical accesses are provided on the seeding unit. Vacuum insulation is also provided for this seeding unit.

The main characteristics of the measurement system are as follows:
- Internal Diameter D = 80 mm
- Beta ratio of the convergent d/D= 0.5
- Length L= 6 D
- Maximum operating pressure = 10 bar

Experiments

The pressurized calibration facility

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) with an relative uncertainty ranging from 0.20 % to 0.25 % depending on the flowrate. A set of twelve Venturi nozzles (nominal flowrate: 1.5 to 1000 $m^3.h^{-1}.bar^{-1}$) 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. The pipe lines bear the reference nozzles chosen according to the flow patterns to be generated for the tests. The longest testing pipeline is 50 m long with nominal diameters from DN25 up to DN300. The meter under test is placed on a pipeline downstream the set of nozzles. 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. A set of control valves placed downstream the tested instrument allows adjustment of the suitable back pressure for calibration [between 1.5 to 10 bar (absolute pressure) for these tests]. Data acquisition and calculations are performed by an automatic computing system. These nozzles are traceable to National Standards by mean of a (P, V, T, time) method.

The cryogenic Measurement system

The model is composed of three parts:
- The cryogenic seeding part
- The conditioning part and the measuring cross-section
- The divergent part.

The seeding part is equipped with an access for the seeding probes in cryogenic conditions, and with two windows for particles visualization.

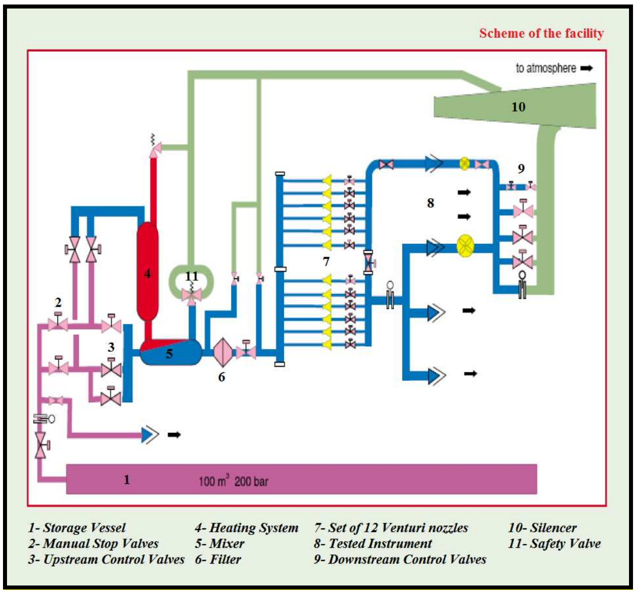

Fig. 1: Pressurized calibration facility (CESAME) .

The conditioning part is composed of a convergent followed downstream with a measurement section provided with windows which allows 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 entire model is equipped with pressure and temperature taps:
- Upstream the convergent (P, T)
- Throat of the convergent (P)
- Downstream the divergent (P, T).

Velocity measurements

The velocity profiles are measured by means of a Laser Doppler Velocimeter DANTEC (Fig.3) in the backscattering mode 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 µm.

For these tests with air under pressure up to 10 bar seeding is done by generating micronic particles of DHES Di (2-ethylhexyl) sebacate, sebacic acid 8D upstreamof the Cryogenic LDV Measurement system.

The assessment of the relative expanded uncertainty on the velocity measured by the LDV gives $U_k(V_{LDV})$= 0.14% (k=2). A comparison of expanded uncertainty estimates of 4 laboratories [6], using the rotating disk for calibration, leads to uncertainty between 0.055% (PTB-Germany) and 0.48% (NIST-USA).

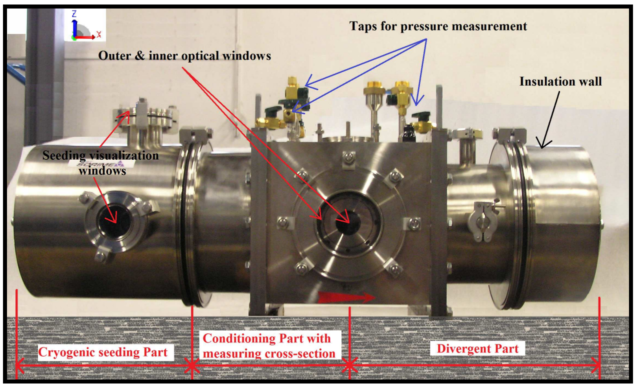

Fig. 2: The cryogenic LDV Measurement system.

Measurement and testing procedure

The testing pipeline (diameter D = 80 mm) is 34D long upstream and 18D long downstream the Cryogenic LDV Measurement System. Due to the spacing between the two laser beams and the focal length, it is not possible to measure complete velocity profiles within 16 mm from the exit of the throat of the convergent. Furthermore, to allow the passage of the laser beams, the measurement section is larger (80 mm) that the section of the throat (d = 40 mm).

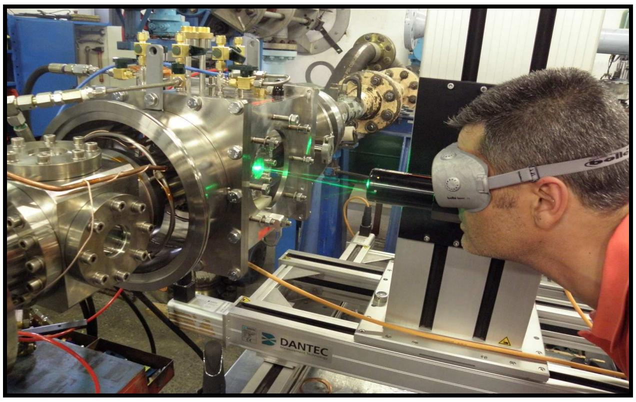

Fig. 3 : LDV System in operation.

Therefore, velocity profiles have been measured between 16 mm and 24 mm from the outlet of the throat with a step of 2 mm, from -40 mm to 40 mm (Y-axis) relative to the axis of the convergent (X-axis). For each test, the velocity on the axis (X-axis) was measured between 12mm and 28 mm from the exit of the throat.

The mean and the RMS velocity profiles are measured in a specific cross-section downstream the throat of the convergent of the Cryogenic LDV Measurement Package for each condition below:

Upstream convergent Pressure	Nominal Velocity at the throat of the convergent without seeding	Reynolds number in the pipe (D = 80 mm)	Mass flowrate through the sonic nozzles
P bar(a)	$\overline{V}$ $m.s^{-1}$	Re_D	Q_m $kg.s^{-1}$
1.5	5	1.0E+04	0.010
	20	4.0E+04	0.045
	57	1.1E+05	0.130
5.0	5	3.3E+04	0.040
	20	1.3E+05	0.150
	57	3.8E+05	0.430
10.0	5	6.5E+04	0.074
	20	2.6E+05	0.300
	57	7.2E+05	0.800

Table 1: Measurement conditions

In addition to the measurement of the mean and the RMS velocity profiles, the following physical quantities are measured:

- Mass Flowrate generated by the reference nozzles chosen according to the flow patterns to be generated for the tests
- Pressure and Temperature upstream of nozzles
- Pressure and Temperature upstream of the convergent
- Differential Pressure between upstream and the throat of the convergent
- Pressure and Temperature downstream of the divergent

For each of the test conditions, the mass flowrate is imposed through sonic nozzles and the upstream pressure is kept constant. The suitable back pressure for each test is adjusted by mean of a set of control valves placed downstream the Cryogenic LDV Measurement Package.

When the flowrate is established, the differential pressure between the inlet and the outlet of the convergent of the Cryogenic LDV Measurement Package is measured without seeding for different Reynolds numbers. In this case, the flowrate measured by means of the sonic nozzle is the reference flowrate, and is used to calibrate the flowrate measured with the differential pressure device of the convergent. If we assume that this flowrate measurement is similar to a venturi tube method [7], from the standard ISO 5167- 4 (venturi tubes) [8], the mass flowrate is expressed:

$$Q_m = C_D \varepsilon \frac{1}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{2\rho\Delta P}$$

The calibration curve $C_D = f(Re_d)$ of the differential device is plotted on Figure 8. This calibration curve of the discharge coefficient C_D versus the throat Reynolds number is used with a process of iterative calculation to determine the total mass flowrate (air + seeding) flowing through the Cryogenic LDV Measurement Package. The assessment of the relative expanded uncertainty on the total reference flowrate measured by means of the convergent gives $U_k(Q_V)$= 0.6% (k=2). The measurement uncertainty of the total reference flowrate should be improved in future experiments.

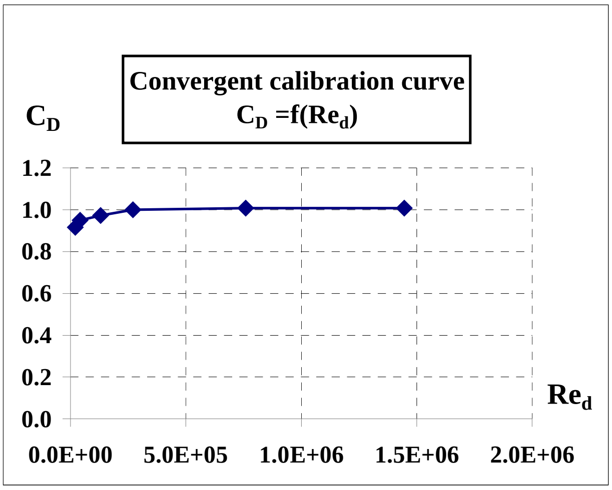

Fig. 4 : Discharge coefficient of the convergent C_D versus the throat Reynolds number - Calibration curve

For each of the test conditions, when the flowrate is established with seeding, the velocity profile is measured a few millimeters downstream the throat of the convergent by means of the LDV system. Simultaneously, the differential pressure is measured between the inlet and outlet of the convergent of the Cryogenic LDV Measurement system. From the calibration curve previously determined, for each of the test conditions, the measurement of the differential pressure is used to calculate the reference mass flowrate at the throat of the convergent.

Results and discussion

Pressure loss of the measurement system

The average total pressure loss ΔP for the Cryogenic LDV Measurement system is expressed as a fraction K of the dynamic throat velocity. For a throat Reynolds number value between $5x10^4$ and $1.5x10^6$, the value of the pressure loss coefficient is K = 0.26. This value is of the same order of magnitude as that of a venturi with a cone angle of 7° and a beta ratio β = 0.5.

Mean velocity and turbulence profiles

For all the tested flow conditions (Pressure = 1.5; 5; 10 bar and throat mean reference velocity = 5; 20; 57 $m.s^{-1}$) typical results are presented in this section [3].

Figure 5 presents the influence of the throat velocity (V_d = 5; 20; 57 $m.s^{-1}$) on the mean velocity profiles V/V_{axis} = f(r/R) downstream the throat (X = 16 mm) and for an absolute pressure P = 5 bar.

All the mean velocity profiles are superimposed except on the outside of the left shear zone. This defect may be due to a leakage problem in the body of the model. The central portions of the velocity profiles are flat and show the action of the convergent. The same characteristics are found for other pressures tested (Fig. 7).

For higher pressures and Reynolds numbers, the flat region increases and the shear zone decreases. This result demonstrates that the influence of the Reynolds number on the velocity profile decreases with this increase.

Figure 6 presents the influence of the throat velocity (V_d = 5; 20; 57 $m.s^{-1}$) on the RMS velocity profiles V_{rms}/V_{axis} = f(r/R) downstream the throat (X = 16 mm) and for an absolute pressure P = 5 bar. All the RMS velocity profiles are very well superimposed. The maximum of the velocity fluctuation corresponds to the zone of maximum shear of the mean velocity profile and is located on a cylinder of the same diameter as the throat, d = 40 mm. The same characteristics are found for other pressures tested (Fig. 8).

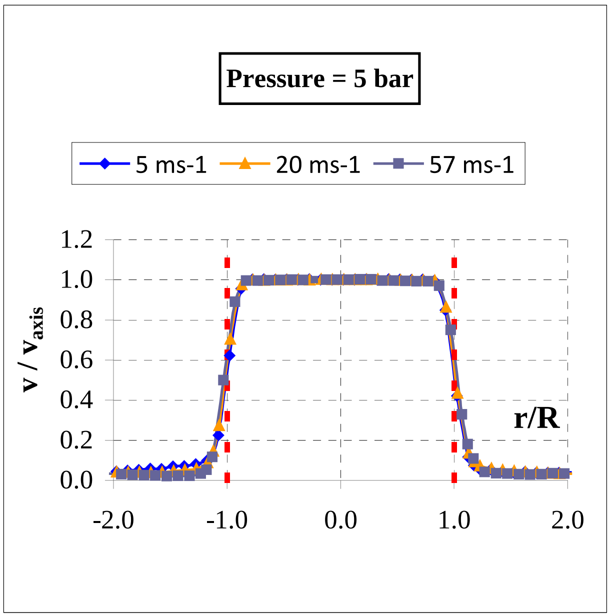

Fig. 5: influence of the throat velocity on the mean velocity profiles downstream the throat
pressure = 5 bar; V_d = 5; 20; 57 $m.s^{-1}$
(--- throat diameter)

Analysis of the LDV measurements

The method to determine the volume flowrate from a local velocity measured downstream of the throat is presented in this section. The basic idea was to design a flow conditioner (convergent) to get a very symmetrical velocity profiles to allow a very repeatable and fast profile measurement. Once the boundary layer has been measured, the volume flowrate measurement can be reduced to a single point measurement (center line velocity measurement):

$$Q_V = \pi R^2 \bar{v}$$

For a given Reynolds number, the output velocity is given by the relation

$$\bar{v} = \frac{4 Q_v}{\pi d^2}$$

and the ratio between the velocity on the axis v_{axis} (measured by the LDV system) and the output velocity $\bar{v}$ is a constant function of the Reynolds number Re_d

$$\frac{V_{axis}}{\bar{v}} = A(Re_d)$$

$$Re_d = \frac{\bar{v}\, d\, \rho}{\mu} = \frac{4 Q_m}{\pi\, \mu\, d}$$

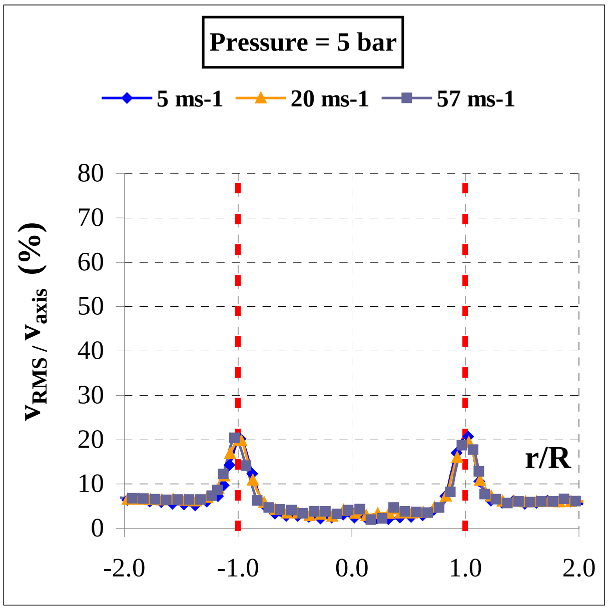

Fig. 6: influence of the throat velocity on the RMS velocity profiles downstream the throat
absolute pressure = 5 bar; V_d = 5; 20; 57 $m.s^{-1}$
(--- throat diameter)

These relations allow the calculation of the volume flowrate from the velocity measured at one point downstream the throat on the axis of the pipe.

$$Q_v = \pi R^2\, \bar{v} = \pi R^2 \frac{V_{axis}}{A(Re_d)}$$

To implement this method, it is necessary to establish the correlation function between the volume flowrate and the local velocity measured and the influence of the Reynolds number.

In all cases tested (throat Reynolds number Re_d between $5x10^4$ and $1.5x10^6$), the reference flowrate Q_{vref}, the mean velocity at the throat section $V_{ref\ mean}$ and the mean axial velocity V_{axis} measured 16 mm downstream the throat by the LDV are determined.

For all pressures, the ratio $V_{axis}/V_{ref\ mean}$ ranges between 1.004 and 1.015 and the dispersion between 0.5 to 2%. If the lowest Reynolds numbers of the order of 10^4 are not taken into account, the mean ratio is of the order of 1.01 and the dispersion 1%. If we take into account that these results are obtained for Reynolds numbers between 10^4 and 10^6 and from an industrial point of view the Reynolds numbers are rather in the range of 10^7 , we can predict the dispersion in these conditions will be reduced. Indeed, for large Reynolds numbers, the velocity profiles are self-similar, and the dispersion of the correlation function $V_{axis}/V_{ref\ mean}$ = $A(Re_d)$ will be reduced.

allow improved accuracy and target uncertainty of 0.2% seems realistic.

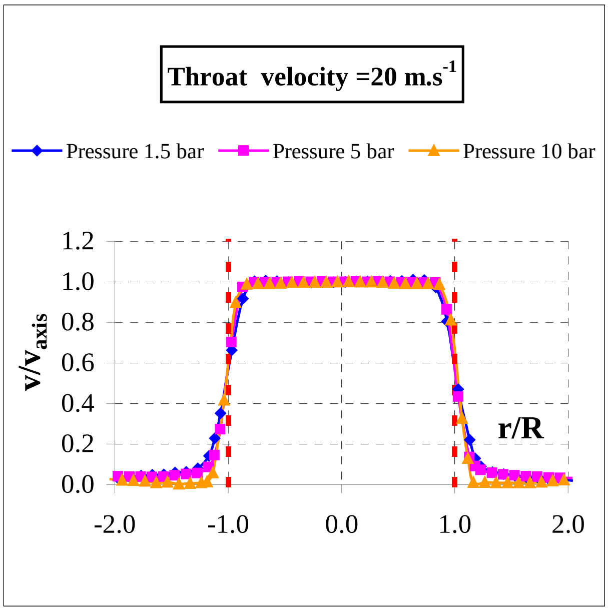

Fig. 7: influence of the absolute pressure on the mean velocity profiles downstream the throat; pressure = 1.5; 5; 10 bar; V_d = 20 $m.s^{-1}$ (--- throat diameter)

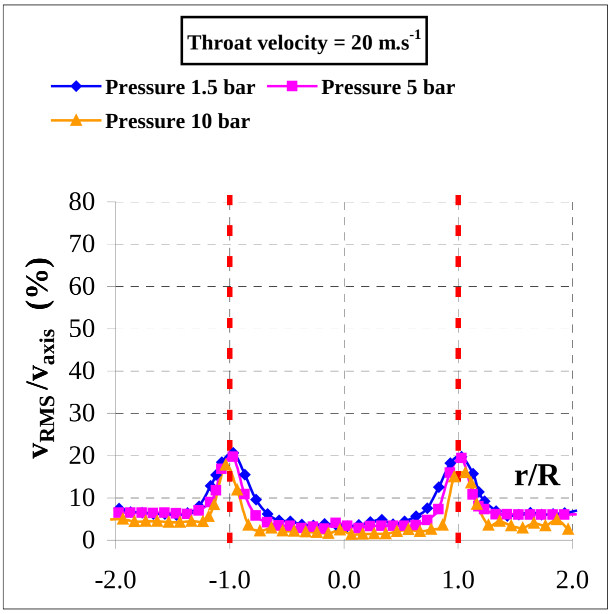

Fig. 8: Influence of the absolute pressure on the RMS velocity profiles downstream the throat; pressure = 1.5; 5; 10 bar; V_d = 20 $m.s^{-1}$ (--- throat diameter)

Discussion

The assessment of the uncertainty on the reference volume flowrate leads to a value of 0.6%. The most important contribution to the overall uncertainty of this calculation comes from the correlation function $A(Re_d)$. It is possible to reduce the uncertainty on the correlation function $A(Re_d)$ by improving the accuracy of the measurement for the reference flowrate in the experiment. Indeed, the accuracy of the latter directly affects the accuracy of the correlation function. On the other hand, the application of this method to industrial conditions leads to Reynolds numbers greater than 10^7. In the case of this feasibility study, the maximum Reynolds number was $1.5x10^6$. The results show that for higher Reynolds numbers, the uncertainty on the correlation function may be significantly reduced. The fundamental interest of this method is that it allows an instantaneous measurement of the volume flowrate and a temporal integration determines the volume of fluid flowing in the pipe during a given time.

Proposals to improve the accuraciy

- Improve the accuracy of determining the correlation function by improving the accuracy on the reference flowrate during the experiments
- Validate by numerical simulation and experiments the beneficial role of Reynolds numbers higher than 10^6-10^7 corresponding to actual industrial Reynolds numbers
- Achieve validation experiments in cryogenic conditions on a calibration facility.

The work carried out shows that an expanded uncertainty of the order of 0.6% on the measurement of volume flowrate can be achieved with this measurement system. Reynolds numbers of about 10^7 in industrial conditions allow improved accuracy and target uncertainty of 0.2% seems realistic.

Conclusion

The feasibility study has shown by preliminary tests realized with pressurized air (1-10 bar) on a simplified prototype of cryogenic LDV measurement system that was possible to measure the flowrate with an accuracy of 0.6% by a local measure of the instantaneous velocity after conditioning the flow.

The air-based experiments achieved at the CESAME laboratory with a throat Reynolds number ranges from $5x10^4$ to $1.5x10^6$ with a simplified Cryogenic LDV measurement system show that the accuracy in real industrial conditions with Reynolds numbers of 10^6-10^7, can achieve relative accuracies of 0.2% under cryogenic conditions with improvements proposed in this study.

This feasibility study demonstrated the potential of this new means of measuring the flowrate of LNG with a direct traceability to SI units. These early experiences help to define future actions to improve performance and accuracy of the cryogenic LDV measurement system:

- Improve the accuracy of the measurement of the reference flowrate to reduce the uncertainty on the criteria to determine the optimal integration limits and on the correlation function.
- Validate by numerical simulation and experiments the beneficial role of Reynolds numbers of the order of 10^6-10^7 to reach a level of uncertainty close to 0.2%.
- Achieved experiments in cryogenic conditions (Liquid Nitrogen & LNG) on a calibration loop.

Finally, the cryogenic LDV measurement system is traceable to SI units (time and length) and use a different technology to the flowrate references (mass and time) used in future calibration facilities for LNG.

This new technology is an alternative method to flowmeters (coriolis, ultrasonic …) used in LNG and it would be useful to validate it in industrial LNG or cryogenic applications.

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